DESIGN AND IMPLEMENTATION OF A MOTOR-DRIVEN IMPEDING FORCE SYSTEM TO UNDERSTAND AND MITIGATE AGE-RELATED DEFICITS IN PUSH-OFF INTENSITY

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ABSTRACT

Katie A. Conway: Design and Implementation of a Motor-driven Impeding Force System to Understand and Mitigate Age-related Deficits in Push-off Intensity
(Under the direction of Jason R. Franz)

Preventing mobility impairment is crucial for our rapidly aging population to lead longer, more independent lives. Walking in older adults is commonly characterized, biomechanically, by deficits in "push-off intensity" - a reduction in ankle moment and power output thought to contribute to slower preferred speeds, and ultimately, reduced independence. Unfortunately, conventional assessments of muscle force-generating capacity fail to fully characterize push-off capacity during walking. Therefore, the mechanisms governing limitations in elderly gait remain unknown. In addition, conventional interventions aimed at enhancing push-off intensity in older adults convey benefits only during maximum speed walking without improving habitual walking speeds or push-off intensity. The first purpose of this dissertation was to engineer and implement a novel system to functionally quantify push-off capacity at the individual limb-, joint-, and muscle-levels during walking. The second purpose was to leverage this system in a 6-week training paradigm designed to improve push-off intensity during walking in older adults.

In study 1, we engineered a biomechanical "stress-test" – a motor-driven, impeding force system that functionally assesses push-off intensity by increasing the propulsive demands of walking. Applying this system in older adults in study 2, we found that, unlike all other biomechanical determinants of push-off intensity, older adults appear unable to overcome their deficits in peak ankle moment during walking, alluding to a genuine functionally limiting

impairment. In study 3, we used *in vivo* imaging to investigate the muscles responsible for generating ankle moments during walking (i.e., plantarflexors). We found that shorter plantarflexor fascicle lengths in older adults associate with worse capacity to enhance push-off intensity in walking. Finally, we tested the efficacy of an impeding force intervention aimed at targeting deficits in push-off intensity. We found that, after 6-weeks of impeding force training, older adults increased plantarflexor strength and cross-sectional area, maximum walking speed, and 6-minute walk distance. Unlike conventional interventions, older adults also increased their ankle power by a significant and clinically-meaningful 12%. Combined, these studies contribute to our mechanistic understanding of deficits in push-off intensity in older adults, and also inform rehabilitation programs towards improvements in independent mobility and quality of life for our aging population.

To Haley.

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CHAPTER 1: INTRODUCTION

Mobility impairment among older adults is extremely prevalent: 17%, 28% and 47% of people aged 65-74, 75-84, and 85+ years respectively report that difficulty walking interferes with daily activities (U.S. Department of Health and Human Services, 2018). In addition to the associated decline in independence and quality of life, compromised walking ability ultimately predicts health and survival in older adults. Older adults who preserve their habitual walking ability (i.e. speed) subsequently experience greater independence, fewer hospitalizations, lower health care costs, and longer lifespan (Friedman, Richmond, & Baskett, 1988; Hardy, Perera, Roumani, Chandler, & Studenski, 2007; Purser et al., 2005).

Characteristics of Aging Gait

Peak ankle moment and power generation during the push-off phase of human walking both contribute to leg swing initiation and forward acceleration of the body's center of mass, thereby playing a pivotal role in regulating step lengths and walking speeds (Zelik & Adamczyk, 2016). Unfortunately, aging and many gait pathologies (e.g., stroke) are characterized by a reduced "push-off intensity" during late stance, which we define at the joint level via peak ankle moment and power generation (i.e., the mechanical output of the plantarflexor muscles) and at the limb level via peak propulsive forces (i.e., the peak anterior component of the horizontal ground reaction force) (Farris, Hampton, Lewek, & Sawicki, 2015; Franz, 2016). These hallmark biomechanical deficits in push-off intensity are thought to contribute to shorter steps, slower preferred speeds, increased metabolic energy cost, and ultimately, reduced independence (Beijersbergen, Granacher, Vandervoort, DeVita, & Hortobagyi, 2013; Franz, 2016). However, there is mounting evidence that many older individuals, after succumbing to reduced plantarflexor mechanical output, retain a reserve capacity to substantially enhance push-off intensity when environmental factors demand, e.g., walking faster (Conway & Franz, 2019), uphill (Conway, Bissette, & Franz, 2018; Franz & Kram, 2013a, 2013b, 2014) or when provided with appropriate biofeedback (Browne & Franz, 2017; Franz, Maletis, & Kram, 2014). Ultimately, this calls into question what the genuine functionally limiting impairments *are* in elderly gait.

Conventional Dynamometry

Unfortunately, conventional methods of quantifying maximum capacity of the plantarflexors, and thus their role as a functionally limiting impairment, (i.e., dynamometry) often fail to capture the functional behavior of these muscles during walking (Conway et al., 2018; Kahn & Williams, 2015; Milot, Nadeau, & Gravel, 2007), especially in older adults (Anderson & Madigan, 2014; Franz, 2016). Conventional investigations into the utilization of propulsive capacity during walking rely on isometric or isokinetic dynamometry to measure muscle strength as a maximum reserve criteria (Anderson & Madigan, 2014; Beijersbergen et al., 2013; Conway et al., 2018; Kahn & Williams, 2015; Milot et al., 2007; Samuel, Rowe, & Nicol, 2013). This isolated contraction ankle moment is then compared to that found during normal walking in order to quantify habitual utilization (%). However, utilization calculated using this approach have previously exceeded 100% in older adults (Anderson & Madigan, 2014), perhaps due to differences in muscle contractile dynamics during isolated contractions compared to more dynamic tasks such as walking. Therefore, there is a critical need for innovation in the assessment of push-off intensity during walking in order to identify genuine functionally-limiting impairments and thereby specific biomechanical targets for clinical intervention.

Functionally Limiting Impairments

Historically, paradigms which increase the propulsive demands of walking have been leveraged to elucidate functional limitations in elderly gait – i.e. the determinants of walking performance that older adults are incapable of increasing. For example, older adults are able to enhance propulsive forces and positive ankle work when walking faster or walking uphill (Conway & Franz, 2019; Franz & Kram, 2013a; Kerrigan, Todd, Della Croce, Lipsitz, & Collins, 1998). However, these studies were conducted at either a fixed grade (Franz & Kram, 2013a, 2014) or subjects were simply instructed to "walk fast" which likely yielded submaximal walking speeds (Kerrigan et al., 1998). Therefore, the extent to which these metrics can potentially be increased is unknown. Similarly, several authors have augmented push-off during treadmill walking via horizontal impeding forces (i.e., "pulling" forces which impede an individual's ability to propel themselves forward), thus systematically increasing the propulsive demands of walking. Previously, however, investigators have prescribed only submaximal levels of impeding forces during walking rather than increasing the propulsive demand to maximum (Danion, Bonnard, & Pailhous, 1997; Farris, 2016; Gottschall & Kram, 2003). Thus, it remains unclear specifically which biomechanical determinants of push-off intensity represent genuine functionally limiting impairments in elderly gait versus, for example, locomotor adaptations that merely *present* as age-related deficits in walking performance. Indeed, elucidating true limitations of elderly gait is critical for the prescription of effective interventions. In order to assess this, we proposed increasing horizontal impeding forces to maximum in older adults, as a biomechanical stress test.

Ultrasound Imaging During Gait

One possible explanation for the reduced push-off intensity exhibited by older adults compared to their young counterparts may lie at the individual muscle-level. The plantarflexor muscles provide the majority of mechanical power needed for forward propulsion during the push-off phase of walking (Francis, Lenz, Lenhart, & Thelen, 2013; Gottschall & Kram, 2003; Neptune, Clark, & Kautz, 2009). Recent advances in ultrasound image analysis have enabled *in vivo* plantarflexor muscle fascicle tracking during functional activities such as walking (Cronin, Carty, Barrett, & Lichtwark, 2011; Farris & Lichtwark, 2016; Farris & Sawicki, 2012). At matched speeds, the soleus muscle fascicles of older adults are shorter across the gait cycle compared to their young counterparts, and undergo less relative shortening (Panizzolo, Green, Lloyd, Maiorana, & Rubenson, 2013). However, the contractile behavior of the uniarticular soleus muscle may differ from the biarticular gastrocnemius muscles, which potentially play a larger role in governing forward propulsion (Francis et al., 2013; Gottschall & Kram, 2003). Older adults' gastrocnemius fascicles have also been found to remain shorter during the gait cycle compared to young adults (Mian, Thom, Ardigo, Minetti, & Narici, 2007). This alludes to the potential for deficits in force production per the force-length properties of muscle (Hill & White, 1968; Rassier, MacIntosh, & Herzog, 1999). For example, if aging muscle fascicles are habitually operating further down the ascending limb, force-generating capacity would be limited compared to young muscle fascicles for the same unit activation. Indeed, in older adults, resting fascicle lengths of the medial gastrocnemius have been correlated with functional walking performance measures such as the 6-minute walk test (Stenroth et al., 2015). However, previous studies have been conducted only during steady-state, habitual walking (Mian, Thom, et al., 2007; Panizzolo et al., 2013), and no study to date has established a mechanistic link between plantarflexor muscle operating behaviour and age-related functional limitations in push-off intensity during walking. Thus, we posit that an age-related shift toward shorter plantarflexor operating lengths, perhaps governed in part by increased tendon compliance, functionally limits force generation and thereby the ability of those muscles to respond to increased propulsive demands during walking.

Conventional Interventions

Unfortunately, the precipitous decline in habitual push-off intensity generated by the plantarflexor muscles for propulsion in walking is highly resistant to conventional intervention (Beijersbergen et al., 2013; Cao, Maeda, Shima, Kurata, & Nishizono, 2007; Granacher, Muehlbauer, Zahner, Gollhofer, & Kressig, 2011; Hartmann, Murer, Bie, & Bruin, 2009; McGibbon, Krebs, & Scarborough, 2003; Mian, Baltzopoulos, Minetti, & Narici, 2007; Persch, Ugrinowitsch, Pereira, & Rodacki, 2009). A common explanation for this clinically-important biomechanical change is that older adults exhibit a loss of skeletal muscle mass (i.e., sarcopenia) (Baumgartner et al., 1998; Bendall, Bassey, & Pearson, 1989; Thelen, Schultz, Alexander, & Ashton-Miller, 1996). Indeed, leg muscle weakness has prompted numerous investigations of resistance training interventions for older adults. However, although resistance and power training improves leg muscle strength and mitigates sarcopenia, strengthening alone generally fails to significantly improve plantarflexor power or preferred walking speed in older adults (Alfieri et al., 2010; Brown & Holloszy, 1991; Daley & Spinks, 2000; Hanson et al., 2009; Nelson et al., 2004; Takeshima et al., 2007; Topp, Mikesky, Wigglesworth, Holt, & Edwards, 1993). In fact, strengthening seems to only convey benefits to maximum speed walking without improving habitual walking speeds (Beijersbergen, Granacher, Gabler, DeVita, & Hortobagyi, 2017). This is likely because resistance training alone is unable to directly encourage access to newfound strength gains. We suspect that preferred walking speed and gait biomechanics in older adults are highly resistant to conventional intervention because of the ingrained nature of habitual locomotor patterns. Therefore, there is a vital need for more targeted strategies designed to purposefully enhance push-off intensity in older adults.

Dissertation Objectives

The purpose of this dissertation was first to investigate push-off intensity at the limb-, joint, and muscle-level during walking in older adults, and thus functionally limiting impairments of elderly gait, and second to test the efficacy of a 6-week impeding force training protocol in improving push-off intensity during walking for older adults. In the first study (Chapter Two), published in the *Journal of Applied Biomechanics*, we investigated the utilization of propulsive capacity during walking in young adults. We engineered a novel system to prescribe a biomechanical stress test as an alternative to conventional dynamometry: horizontal impeding forces designed to increase the propulsive demands of walking to their maximum. We then sought to leverage this methodology in an older adult population to investigate functionally limiting impairments at the limb- and joint-level in elderly gait (Chapter Three), a study that was published in the *Journal of Aging and Physical Activity*. In Chapter Four, which was published in *Gait and Posture,* we investigated potential muscle-level mechanisms responsible for push-off intensity in aging gait. Finally, applying our improved mechanistic understanding, we designed and implemented a 6-week impeding force training protocol and tested its efficacy in enhancing biomechanical push-off intensity in older adults (Chapter Five). Together, these studies contributed to our mechanistic understanding of deficits in push-off intensity in older adults at the overall limb-, joint-, and muscle-level. In addition, these studies are intended to inform clinical training programs which could contribute to improvements in independent mobility, and ultimately, quality of life for our aging population. The broader implications of this work extend to clinical populations which exhibit similar hallmark deficits in push-off intensity (e.g., cerebral palsy, multiple sclerosis and persons following stroke).

CHAPTER 2: THE FUNCTIONAL UTILIZATION OF PROLUSIVE CAPACITY DURING HUMAN WALKING[1]

INTRODUCTION

Peak ankle moment and power generation during the push-off phase of human walking both contribute to leg swing initiation and forward acceleration of the body's center of mass, thereby playing a pivotal role in regulating step lengths and walking speeds (Zelik & Adamczyk, 2016). Unfortunately, aging and many gait pathologies (e.g., stroke) are characterized by a reduced "push-off intensity" during late stance, which we operationally define here at the joint level via peak ankle moment and power generation (i.e., the mechanical output of the plantarflexor muscles) and at the limb level via peak propulsive forces (i.e., the peak anterior component of the horizontal ground reaction force) (Farris et al., 2015; Franz, 2016). This biomechanical deficit in push-off intensity is thought to contribute to shorter steps, slower preferred speeds, increased metabolic energy cost, and ultimately, reduced independence (Beijersbergen et al., 2013). However, there is mounting evidence that many individuals, after succumbing to reduced plantarflexor mechanical output, retain a neuromuscular reserve for enhancing push-off intensity during walking that goes underutilized for reasons that are poorly understood (Franz, 2016). Moreover, conventional interventions aimed at enhancing ankle moment and power generation and thus walking speed

[1] This chapter previously appeared as an article in the *Journal of Applied Biomechanics*. The original citation is as follows: Conway, K. A., Bissette, R. G., & Franz, J. R. (2018). The Functional Utilization of Propulsive Capacity During Human Walking. *Journal of Applied Biomechanics*, 1-31. doi:10.1123/jab.2017-0389

(e.g., muscle strengthening or power training) seem to convey benefits only during maximum speed walking (Beijersbergen et al., 2017). Thus, measures of push-off intensity available during maximum speed walking are likely distinct from those habitually utilized or available at preferred speeds. As we elaborate in more detail below, conventional dynamometry, an approach that attempts to characterize the maximum capacity of muscles spanning the ankle, may underestimate the mechanical output of those muscles available during walking (Anderson & Madigan, 2014). Together, these findings imply that our understanding of the functional utilization of propulsive capacity (i.e., the maximum available peak propulsive force, peak ankle moment, and peak ankle power, **Fig. 1A**) at preferred speeds, and thus changes thereof due to aging and gait pathology, is fundamentally incomplete. We propose that a functional assessment of reserves available to enhance push-off intensity during the push-off phase of walking could empower the discriminate prescription of gait interventions that target plantarflexor mechanical output and thereby improve translational outcomes.

Reduced mechanical output of the plantarflexor muscles during push-off, and thus reduced propulsive forces, are hallmark biomechanical features of elderly gait as well as gait pathology such as that following stroke (Farris et al., 2015; Franz, 2016). Candidate mechanisms governing those changes include reduced muscle size and force-generating capacity and/or altered neural control of distal leg muscles – unfavorable changes that are certain to place functional limitations on maximum walking speed (Baumgartner et al., 1998). It is less clear what governs push-off intensity or the available capacity thereof during walking at preferred speeds. For example, when walking at a submaximal speed near the preferred speed normally reported for older adults, many older adults retain the potential to enhance metrics of push-off intensity to values that are indistinguishable from or even significantly greater than those seen in young adults walking at the same speed (Franz et al., 2014). This is also evident when walking uphill, wherein older adults retain the capacity to increase propulsive forces by 69%, positive ankle work by 55%, and plantarflexor muscle activities by 75%-136% compared to level ground walking (Franz & Kram, 2013a, 2013b, 2014). Similarly, Wang et al. (2015) recently found that walking speed in more than half of their cohort of stroke survivors was relatively insensitive to the application of a constant horizontal impeding force (i.e., forces that impede forward acceleration of the body's center of mass). Those authors interpreted their findings to suggest that these individuals may have an available but underutilized reserve capacity to enhance push-off intensity when walking at their preferred speed.

Conventional methods used to assess the functional utilization of muscles that govern push-off intensity in walking, such as isokinetic or isometric dynamometry, likely fail to characterize the physiology of muscle force or power generation during functional activities like walking. This is especially notable when assessing plantarflexor mechanical output, which often yields physiologically implausible (i.e., ≥100%) values of 'functional capacity utilized (FCU)', most frequently defined as the ratio of the peak ankle moment during the push-off phase of walking to that during a maximum isometric voluntary contraction (Anderson & Madigan, 2014; Beijersbergen et al., 2013; Milot, Nadeau, & Gravel, 2007). We are certainly not the first to acknowledge the critical need to distinguish functional propulsive capacity and its utilization, for example during walking, from isolated muscular capacity assessed via strength measurements. Recently, for instance, Kulmala et al. (2016) used a two-legged maximal jump as an alternative, and more functional, approach for assessing maximal capacity as a reference for muscle function in walking. However, peak ankle moment and power developed during maximum height jumping involves muscle contractile dynamics and series elastic energy storage and return that is altogether different from those in walking. In the studies by Wang et al. (2015) and others (Danion et al., 1997; Farris, 2016; Gottschall & Kram, 2003), horizontal impeding forces have been used to systematically increase the propulsive demands of walking – either at submaximal levels during preferred speed walking or while covarying walking speed using a self-paced treadmill. However, no study to our knowledge has used horizontal impeding forces to quantify maximum propulsive capacity during walking at preferred speeds and the functional utilization thereof. Indeed, as an alternative to dynamometry, the strategic use of horizontal impeding forces may offer a more functional assessment of propulsive reserves during the push-off phase of walking with important translational implications.

As an important first step, our purpose was to use a custom impeding force system to improve our joint-level understanding of the functional utilization of propulsive capacity during human walking in young subjects, with an emphasis on the plantarflexor muscles. We first hypothesized that young adults retain reserve capacities for increasing their peak propulsive force, peak ankle moment, and peak ankle power at a preferred walking speed that are positively correlated with those available to increase walking speed to its maximum. Second, we hypothesized that plantarflexor FCU (%) values derived from a maximum impeding force protocol would be both lower and more plausible than those obtained using conventional dynamometry. As a secondary aim, we quantified corresponding changes to hip joint moment and power generation. Indeed, young adults exhibit disproportionately greater increases in hip power generation to meet the propulsive demands of uphill walking (Franz & Kram, 2014; Lay, Hass, & Gregor, 2006) and people with reduced push-off intensity exhibit a well-documented distal-to-proximal redistribution of leg muscle function compared to young controls (Beijersbergen et al., 2017; DeVita & Hortobagyi, 2000; Judge, Davis, & Ounpuu, 1996; McGibbon et al., 2003; Winter, Patla, Frank,

& Walt, 1990). Thus, we finally hypothesized that hip mechanical output would increase more in response to completing a ramped impeding force protocol than during maximum speed walking.

METHODS

Subjects

Twelve young adults participated (age: 24.4±5.7 years, height: 1.79±0.1 m, mass: 74.0±9.7 kg, 7M/5F). The protocol was approved by the UNC IRB and all subjects provided written informed consent prior to participating. We excluded subjects with known neurological impairment and/or musculoskeletal injury in the previous 6 months. Prior to all testing, we quantified subject's preferred ("Pref", 1.3±0.2 m/s) and maximum safe ("Fast", 2.5±0.3 m/s) walking speeds as the average of three times taken to traverse the middle 2 m of a 10 m overground walkway.

Impeding Force System

In one walking trial, subjects wore a waist belt centered around their pelvis that connected via steel cable to a feedback-controlled, motor-driven, impeding force system capable of prescribing horizontal impeding forces according to instantaneous measurements from a load cell (Futek, Irvine, CA) (**Fig. 1B**). An in-series servo motor (Kollmorgen, Radford, VA) combined with a 10:1 gearhead (Thomson Micron, Radford, VA) could provide a peak torque of 44 Nm, corresponding to up to, if desired, a 924 N impeding force. The motor is housed in a height-adjustable frame composed of 38 mm × 38 mm extruded aluminum bars.

Real-time modulation of the instantaneous impeding force was regulated via a customized LabVIEW interface, implemented on a standard PC and a processor-based motor controller (NI PCI 7352, National Instruments, Austin, TX). Specifically, the controller updates the set point position of the motor in proportion to the difference between the instantaneous load cell signal and the desired impeding force level. In this experiment, the desired impeding force level was time-varying, increasing in a linear ramp from zero at rate of 1 %BW/s, systematically increasing the propulsive demands of each step until the respective walking trial completed (**Fig. 1B**), as described in more detail below. Representative time series data from a subject walking under this condition is included (**Fig. 2**).

Treadmill Walking Trials

Subjects completed all walking trials on a dual-belt, force-measuring treadmill (Bertec, Corp. Columbus, OH). First, subjects walked for 1 min at their preferred overground speed ("Pref"). Then subjects walked at this same speed while our system applied the linear ramp increase in impeding force described earlier ("Ramp"). Here, we instructed subjects to maintain their position on the treadmill throughout the ramped protocol while avoiding excessive forward lean. Subjects were verbally encouraged to reach maximum exertion and the trial ended following an inexorable 0.35 m (~1/2 treadmill length) posterior translation of the subjects' pelvis relative to the starting position, monitored using the motor's encoder (**Fig. 1B**). Finally, subjects completed a trial in which they increased their speed from rest to their maximum overground walking speed on the treadmill, which they then maintained for approximately 10 seconds ("Fast"). We thoughtfully selected the order of these experimental trials for two reasons. First, subjects completed the preferred walking trial before the impeding force Ramp and Fast trials to avoid the potential influence of either maximum exertion on baseline measurements. Second, subjects completed the impeding force Ramp before the maximum speed walking trial to ensure that subjects were fully capable of reaching their functional propulsive capacity – the key novel contribution of this study - without being affected by the maximum speed trial.

Dynamometry

In order to compare to more conventional assessments of muscular capacity, we recorded subjects' maximum voluntary isometric ankle moment using a dynamometer (Biodex Medical Systems, Shirley, NY) set to a neutral ankle angle of 0° for all subjects using a goniometer – corresponding to the nominal timing of peak ankle moment and power generation during the push-off phase of walking. Similarly, all subject's knee angle approximated that at the same instant of walking (~20°). Straps over the foot and thigh restricted motion to ankle plantarflexion/dorsiflexion. Subjects were verbally encouraged to reach their maximum in a series of two, 4-second ramped contractions separated by at least one minute.

Measurement and Analysis

For all treadmill trials, a 14-camera motion capture system (Motion Analysis, Corp., Santa Rosa, CA) recorded the 3D trajectories of 31 retroreflective markers (100 Hz) on the pelvis and lower limbs in synchrony with 3D ground reaction force data recorded at 1000 Hz. These data were filtered using 4^{th} order low-pass Butterworth filters with cutoff frequencies of 6 Hz and 100 Hz, respectively. We used a standing trial and functional hip joint centers from right and left leg circumduction tasks (Piazza, Okita, & Cavanagh, 2001) to scale a seven segment, 18 degree-of-freedom model of the pelvis and lower limbs (Arnold, Ward, Lieber, & Delp, 2010). Finally, we used these scaled models and an inverse dynamics routine described in detail previously to estimate leg joint kinematics, moments, and powers (Silder, Heiderscheit, & Thelen, 2008). For Pref, we time-normalized and averaged all strides taken in the 1-minute walking trial. For both other conditions (i.e. Ramp, and Fast), we extracted all outcome measures from the single right stride associated with the largest peak anterior (i.e., propulsive) ground reaction force to best associate with the right-side dynamometry and electromyographic (EMG) data.

Additionally, we collected EMG recordings from wireless electrodes (Delsys Trigno, Natick, MA) placed over the right lateral gastrocnemius and soleus muscles using conductive gel. EMG data were demeaned, rectified, and band-pass filtered (20-400 Hz) and normalized to the average values obtained during normal walking. For Pref we analyzed stride-averaged EMG data. For Ramp and Fast, we extracted EMG data from the single right stride associated with the largest propulsive force using the same methodology described above. For all conditions, we derived 10 Hz low-pass linear envelopes for each muscle from which we extracted mean values between 30 and 60% of the gait cycle (i.e. the second half of stance) (Perry & Burnfield, 2010).

We defined subjects' maximum isometric ankle moment from the dynamometry data as the peak generated during the isometric contraction, averaged across the two repetitions. Finally, we sought to quantify subjects' relative utilization of their maximum available peak ankle moment during normal walking at their preferred speed. Specifically, we calculated subjects' FCU (%) as the ratio of peak ankle moment during Pref to that resolved from: (i) dynamometry, (ii) Ramp, and (iii) Fast. For example, an FCU of 80% would imply that an individual was using 80% of their maximum capacity, while retaining a reserve of 20% (**Fig. 1A**).

Statistical Analysis

Our primary outcome measures included peak propulsive force, local minima and maxima extracted from hip and ankle kinematic (whole gait cycle) and kinetic (stance phase only) time series, average push-off lateral gastrocnemius and soleus EMG, and FCU outcomes. First, a repeated measures ANOVA tested for significant main effects of condition (Pref, Ramp, Fast) on each outcome measure using an alpha level of 0.05. When a significant main effect was found, post-hoc pairwise comparisons identified significant differences between conditions. Finally, we calculated Pearson correlation coefficients for each of our primary outcome measures (i.e., peak propulsive force, ankle moment, ankle power, and lateral gastrocnemius and soleus EMG) between (i) Ramp and Fast and (ii) changes in those outcome measures when we increased the propulsive demands of walking from Pref to either maximum Ramp or maximum speed.

RESULTS

We found a significant main effect of condition for peak propulsive force and plantarflexor neuromechanical outcome measures (all p-values<0.001). Compared to walking normally at their preferred speed, peak propulsive forces, ankle moment, and ankle power increased by an average of 66% (31.7±6.9 %BW vs. 19.2±2.9 %BW), 33% (1.6±0.3 Nm/kg vs. 1.2±0.2 Nm/kg), and 107% (5.4±2.0 W/kg vs. 2.6±0.7 W/kg) (p<0.001) respectively, when subjects walked at their maximum speed (**Figs. 2 and 4**). These values increased by 90% (36.5±5.9 %BW vs. 19.2±2.9 %BW), 20% (1.4±0.2 Nm/kg vs. 1.2±0.2 Nm/kg), and 56% (4.1±1.35 W/kg vs. 2.6±0.7 W/kg), respectively, for maximum Ramp (p<0.001), a condition that lasted, on average, 21.5±8.5 s (i.e., 21.5 %BW following the 1 %BW/s prescribed in our protocol). Peak ankle moment generated during maximum Ramp was nearly indistinguishable from that during maximum speed walking (p=0.271). These kinetic changes were accompanied by significant increases in peak ankle dorsiflexion (p≤0.001) and plantarflexion (p<0.019) for both conditions compared to Pref (**Fig. 5**). Pairwise comparisons showed significant differences between Ramp and Fast ankle dorsiflexion (p<0.001) but not plantarflexion (p=0.222). Also compared to Pref, lateral gastrocnemius EMG during push-off increased by an average of 430% (130%) and soleus EMG by an average of 287% (119%) for Ramp (Fast) (p<0.005) (**Fig. 6**). Lateral gastrocnemius (p=0.014) and soleus (p=0.003) EMG were also higher for Ramp versus Fast.

Peak ankle moment and power (r=0.82, p=0.001 and r=0.64, p=0.026, respectively), but not peak propulsive forces (p=0.099), were significantly and positively correlated between the Ramp and Fast conditions. However, subjects only modulated the change in peak ankle moment to reach maximum Ramp in proportion to that to reach maximum speed (r=0.74, p=0.006). Indeed, we found no significant correlation between the relative change in ankle power (r=0.35, p=0.261) nor peak propulsive force (r=0.49, p=0.110) for these two conditions compared to Pref (**Fig. 7**). We also found no significant correlations for any EMG outcome measure.

For those we could directly compare, FCU (%) values derived from the impeding force protocol and maximum speed walking were lower and more plausible than those obtained using conventional dynamometry. For peak propulsive forces, FCU averaged 51±12% and 61±17% for walking at preferred speed compared to maximum ramp and maximum speeds, respectively (i.e. Pref/Ramp and Pref/Fast, %). These values averaged 57±12% and 53±18%, respectively, for peak ankle power. Ankle moment utilization during Pref resolved using reference values from Ramp and Fast averaged only 78±12% and 76±13%, respectively – values that did not significantly differ from one another (p=0.425). In contrast, maximum isometric ankle moments yielded FCU values of 115±42% and 152±55% for walking at preferred and maximum speeds, respectively (i.e. Pref/Dynomometry and Fast/Dynomometry). Pairwise comparisons revealed that dynamometry significantly overestimated both ankle moment FCU values acquired during walking (p≤0.006).

We found a significant main effect of condition on all hip kinematic and kinetic outcome measures (p<0.001). Compared to Pref, peak hip extensor moment during early stance increased on average by 143% (0.5±0.2 Nm/kg vs. 1.3±0.5 Nm/kg) and 167% (0.5±0.2 Nm/kg vs. 1.4±0.5 Nm/kg) for Ramp and Fast, respectively (p<0.001) (**Fig. 4**). These changes were accompanied by 463% (2.2±0.9 W/kg vs. 0.4±0.3 W/kg) and 411% (2.0±0.94 W/kg vs. 0.4±0.3 W/kg) increases in peak hip extensor power ($p<0.001$). During terminal stance, peak hip flexor moment differed significantly from Pref only for Fast (increased, $p<0.001$). Also during terminal stance, peak hip flexor power increased by, on average, 75% (2.8±1.3 W/kg vs. 1.6±0.5 W/kg) and 215% (5.0±2.3 W/kg vs. 1.6±0.5 W/kg) for Ramp and Fast, respectively, compared to Pref ($p<0.001$) (**Fig. 4**). Pairwise comparisons revealed larger hip flexor power for Fast than for Ramp ($p=0.046$). Finally, we found no significant effect of condition on peak hip extension ($p=0.075$). However, peak hip flexion during terminal swing increased significantly for all conditions compared to Pref ($p<0.005$) (**Fig. 5**).

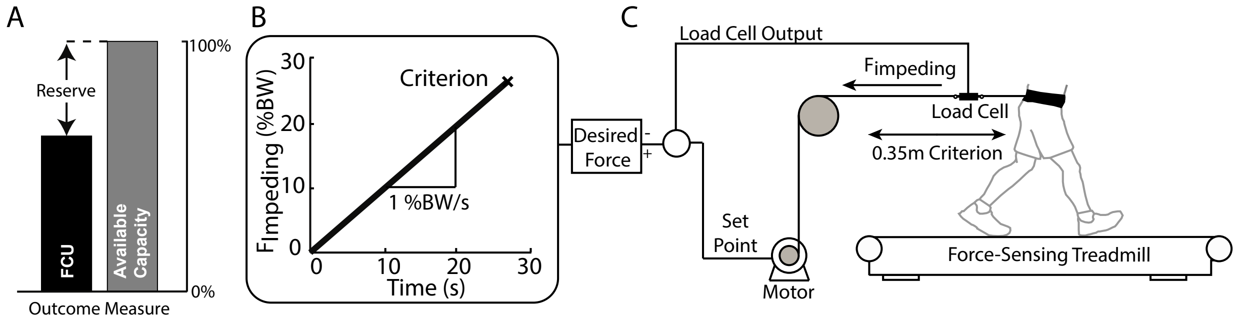

Figure 1: (A) Schematic operationally defining functional capacity utilized (FCU) and reserve capacity available to enhance push-off intensity during walking compared with maximum available capacity, reported as a percentage. **(B)** In one walking trial, subjects wore a waist belt that connected horizontally via a stainless-steel cable to a feedback controlled, motor-driven, impeding force system capable of prescribing horizontal impeding forces via a motor according to instantaneous measurements from a load cell. Specifically, we used a novel ramped impeding force protocol that increased at a rate of 1 %BW/s until the subjects reached the criterion for ending the trial, an inexorable 0.35 m posterior displacement of the subjects' pelvis.

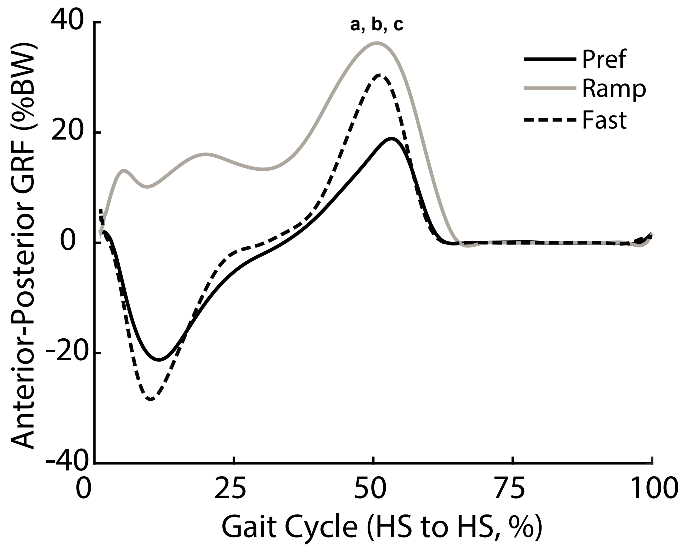

Figure 2: Group mean anterior-posterior ground reaction forces for preferred (Pref), maximum ramp (Ramp) and maximum speed walking (Fast). We statistically compared the peak propulsive force (i.e., the peak anterior component during late stance). In the event a significant main effect of condition ($p<0.05$), significant pairwise comparisons are noted as follows: [a]Ramp versus Pref, [b]Fast versus Pref, and [c]Ramp and Fast. HS: heel-strike.

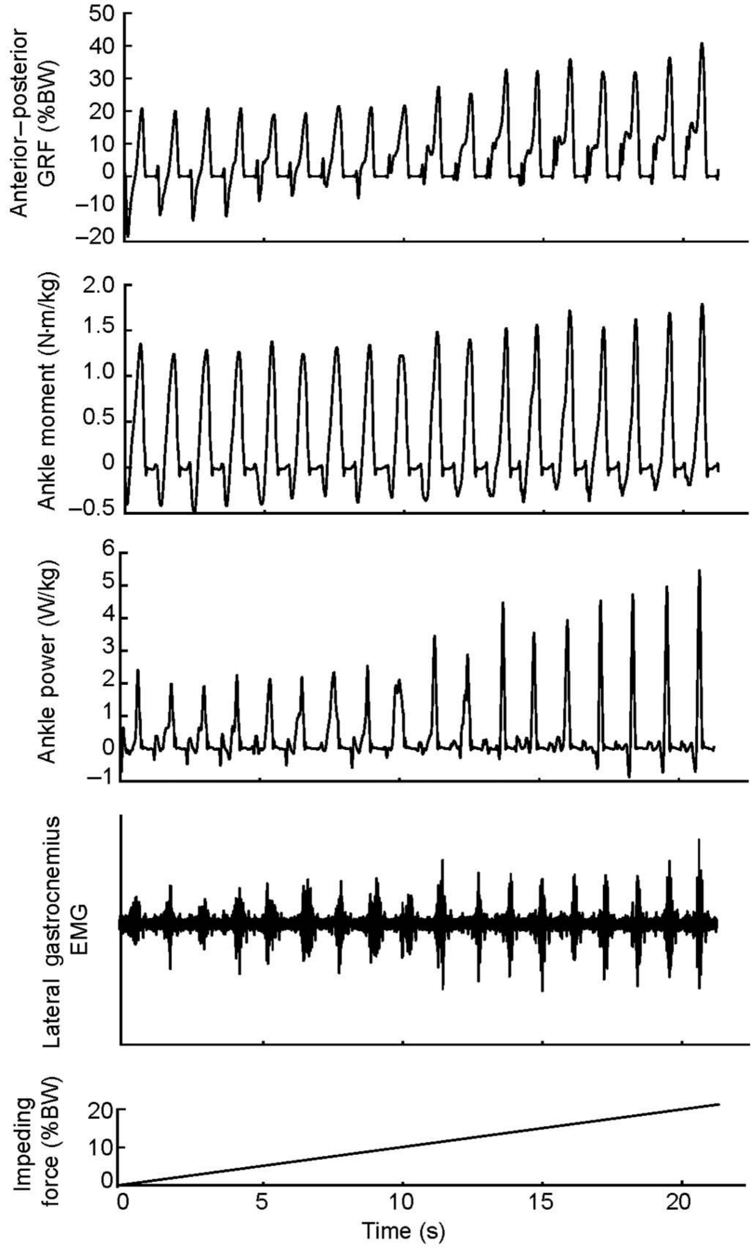

Figure 3: Representative subject completing the impeding force Ramp condition showing time series of anterior-posterior ground reaction force, ankle moment, ankle power and lateral gastrocnemius activity, and applied impeding force.

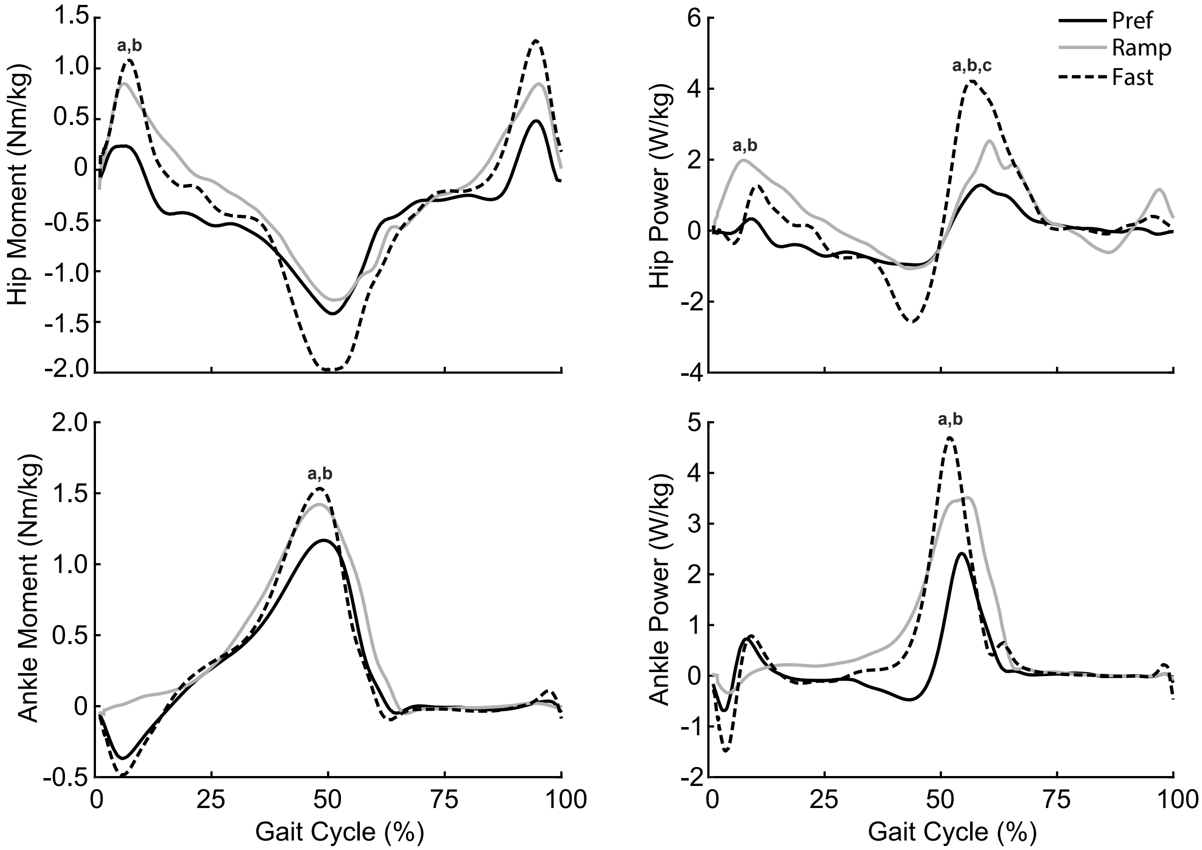

Figure 4: Group average hip and ankle joint moments and powers plotted against an averaged gait cycle, from heel-strike to heel-strike, for preferred (Pref), maximum ramp (Ramp) and maximum speed walking (Fast). Positive values indicate internal hip extensor and ankle plantarflexor moments or power generation. In the event a significant main effect of condition on local maxima or minima ($p<0.05$), significant pairwise comparisons are noted as follows: [a]Ramp versus Pref, [b]Fast versus Pref, and [c]Ramp versus Fast. HS: heel-strike.

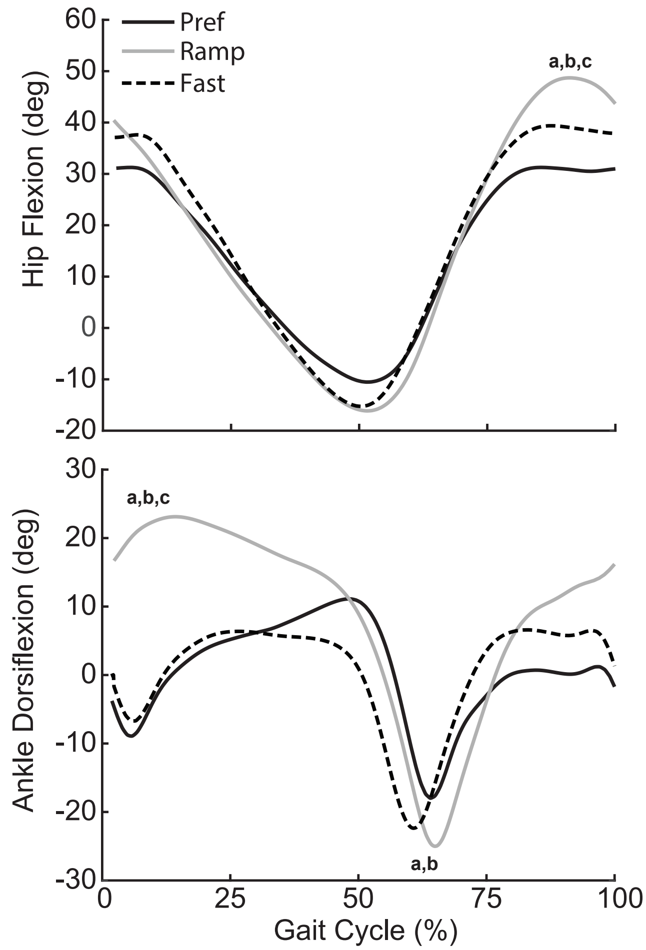

Figure 5: Group average hip and ankle joint kinematics plotted against an averaged gait cycle, from heel-strike to heel-strike, for preferred (Pref), maximum ramp (Ramp) and maximum speed walking (Fast) trials. Positive values indicate hip flexion and ankle dorsiflexion. In the event a significant main effect of condition on local maxima or minima ($p<0.05$), significant pairwise comparisons are noted as follows: [a]Ramp versus Pref, [b]Fast versus Pref, and [c]Ramp versus Fast. HS: heel-strike.

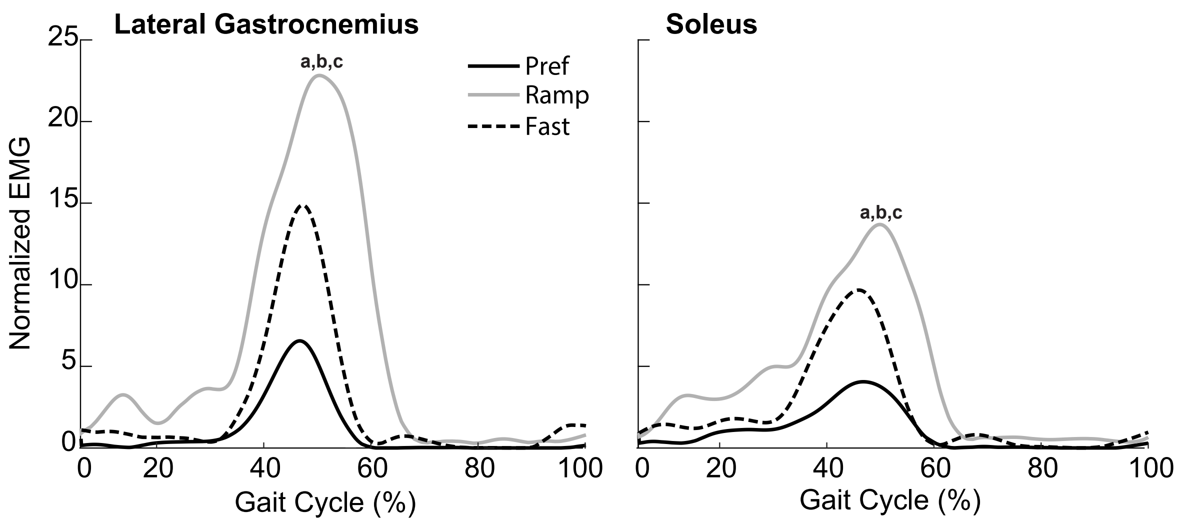

Figure 6: Group average electromyographic (EMG) recordings from the right lateral gastrocnemius and soleus plotted against an averaged gait cycle, from heel-strike to heel-strike, or preferred (Pref), maximum ramp (Ramp) and maximum speed walking (Fast) trials. EMG amplitudes were normalized to the average value over a complete stride during preferred speed walking. In the event a significant main effect of condition on local maxima or minima ($p<0.05$), significant pairwise comparisons are noted as follows: [a]Ramp versus Pref, [b]Fast versus Pref, and [c]Ramp versus Fast. HS: heel-strike.

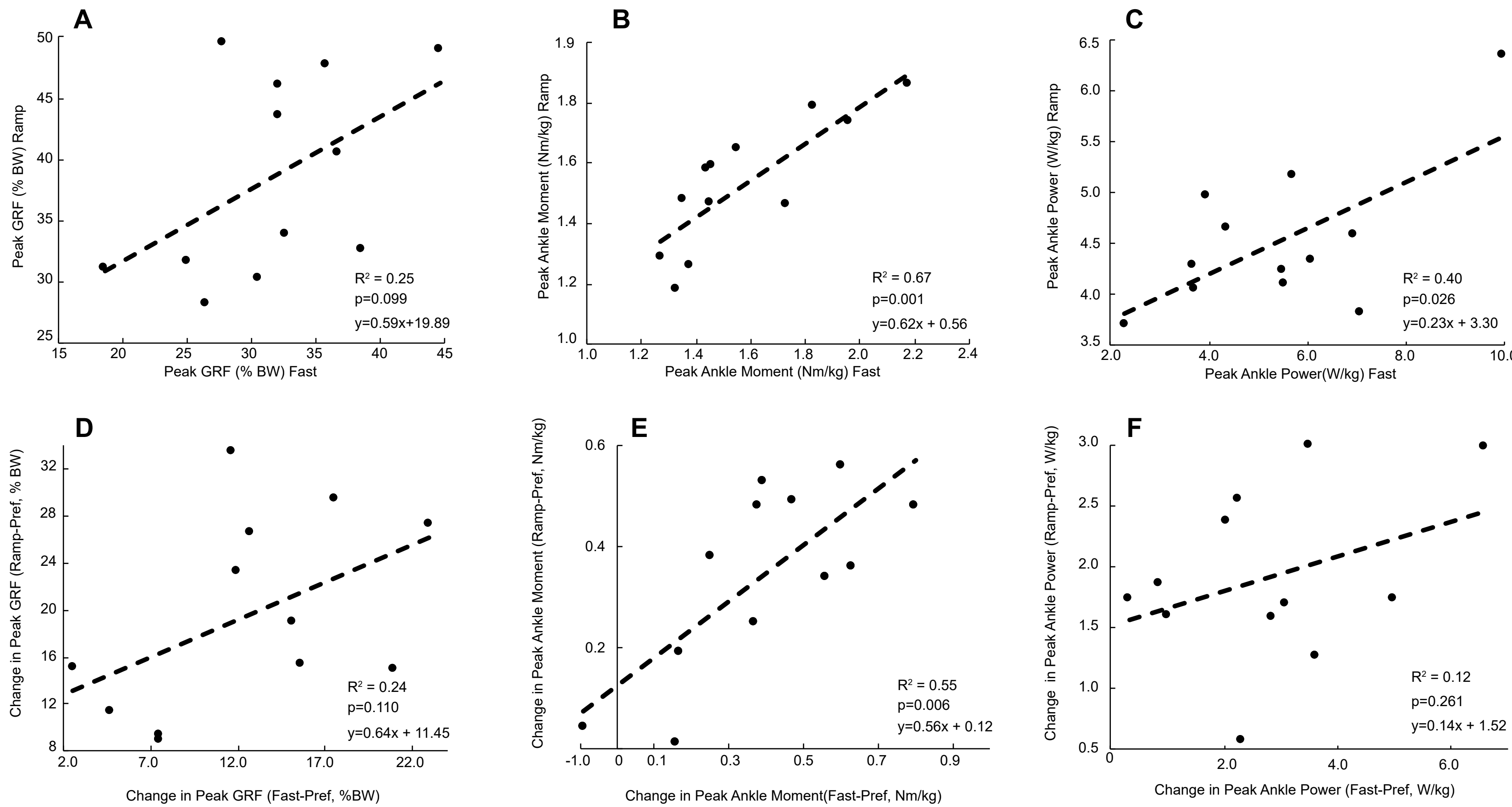

Figure 7: (A-C) Bivariate correlations between peak outcome measures (i.e. peak propulsive force, peak ankle moment, and peak ankle power) from the maximum Ramp condition versus that from maximum speed walking (Fast). The black line represents the best-fit linear regression. **(D-F)** Bivariate correlations between the change in these peak outcome measures from preferred walking for the maximum Ramp condition (Ramp-Pref) versus that for maximum speed walking (Fast-Pref). The black line represents the best-fit linear regression.

DISCUSSION

This study sought to provide functional insight into the utilization of propulsive capacity during the push-off phase of human walking**.** Using a novel ramped impeding force protocol, we discovered that young subjects walking at their preferred speed retain a reserve capacity (i.e., 100%-FCU) for exerting larger peak propulsive forces of 49%, peak ankle moment of 22%, and peak ankle power of 43% during push-off. In partial support of our first hypothesis, young adults retained a capacity for increasing peak ankle moment and power at their preferred speed which positively correlated with that available to increase walking speed to a maximum. Similarly, in the context of those correlations, our data suggest that these reserve capacities are governed at least in part by the contractile behavior (i.e. fascicle operating length and velocity) of the plantarflexor muscles, evidenced by similar peak ankle moments, though not power nor activation, at subjects' maximum walking speed versus during a maximum impeding force protocol. In addition, as we elaborate more below, another major contribution of this study was that these reserves went altogether overlooked when assessed via conventional dynamometry. In fact, ankle moment FCU values calculated in the conventional manner (i.e., using dynamometry) far exceeded values that we would consider physiologically plausible, a critical limitation overcome using a maximum impeding force paradigm during walking. Ultimately, the reference data presented here pave the way for future studies on aging or gait pathology. Indeed, insight into the magnitude of propulsive capacity reserves would empower the more discriminate and personalized prescription of gait interventions seeking to improve push-off intensity and thus walking performance.

Our empirical data suggest that the capacity of young adults to respond to a maximum impeding force protocol or to increase walking speed to its maximum may be governed by the neuromechanical behavior of the plantarflexor muscles. Indeed, the plantarflexor muscles generate as much as 80% of the mechanical power needed during push-off for leg swing initiation and forward acceleration of the body's center of mass (Farris & Sawicki, 2012). Moreover, prior studies have implicated the operating behavior of the plantarflexor muscles in prescribing the walk-to-run transition (Neptune & Sasaki, 2005) and maximum walking speeds (Clark, Manini, Fielding, & Patten, 2013). More recently, Hsiao et al. (2015) added that, in addition to trailing limb extension, peak ankle moment during push-off is a major contributor to peak propulsive forces generated during walking (Hsiao, Knarr, Higginson, & Binder-Macleod, 2015). Consistent with these results, we add that peak ankle moment was nearly indistinguishable between walking in response to a maximum impeding force protocol and walking at maximum speed. We interpret these data, particularly when placed in the context of the correlations we discuss below, to suggest that plantarflexor contractile behavior may be a governing factor in regulating both maximum speed during human walking and the ability to increase propulsive force generation during a maximum impeding force condition. Interestingly, compared to normal walking, plantarflexor activation increased most when increasing propulsive force when completing the maximum impeding force protocol, while peak ankle power increased most when increasing walking speed to maximum. One challenge is that EMG activity can vary with ankle angle (which differed in flexion between the Ramp and Fast conditions) due to changes in the muscle operating lengths (Arampatzis et al., 2006; Kubo, Tsunoda, Kanehisa, & Fukunaga, 2004). Indeed, ankle angle significant differed between the Ramp and Fast conditions. These results highlight an opportunity to couple our experimental paradigm with ultrasound-based muscle fascicle measurements to gain additional insight.

Correlations between young adults' reserve capacity to complete a maximum impeding force protocol at their preferred walking speed and that to increase walking speed to maximum bolster our understanding of the functional utilization of propulsive capacity during human walking. We first found that, as hypothesized, young adults most capable of exerting larger peak ankle moments and power generation when walking at their maximum speed were also those capable of doing so when responding to the prescribed maximum impeding force protocol. This outcome for ankle power is particularly interesting; ankle power is highly dependent on joint angular velocity and thus sensitive to walking speed. Thus, it may not be otherwise intuitive to suspect significant correlations between Ramp and Fast given such a large difference in walking speeds. However, considering relations between our Ramp and Fast conditions alone may neglect the extent to which young adults instinctively utilize their maximum available peak ankle moment and/or power generation during normal walking. Consistent with this premise, the change in peak ankle moment from normal walking, but not that in ankle power, exhibited a significant positive correlation between the ramped impeding force protocol and maximum speed walking. Our results suggest that, unlike peak ankle power, the utilization of peak ankle moment may scale to an individual's maximum available ankle moment capacity during walking. Accordingly, maximum speed walking may prove to be an easily implemented functional test to approximate the maximum available and functional utilization of peak ankle moment. In contrast, the utilization of ankle power generation – a critical determinant of walking performance and economy that is disproportionately afflicted by aging and gait pathology (Farris et al., 2015; Franz, 2016) - remains less clear. Measuring that utilization directly during preferred speed walking, for example through the use of impeding forces, may be translationally important.

Several prior studies have used conventional dynamometry to assess the functional utilization of muscles that govern push-off intensity in walking (Anderson & Madigan, 2014; Beijersbergen et al., 2013; Milot et al., 2007). Common to these studies, the plantarflexor muscles operate closer to their maximum isometric capacity than extensor muscles spanning the knee or hip. However, there are increasing calls for assessment techniques that better replicate the physiology of muscle force and/or power generation during functional activities like walking (Beijersbergen et al., 2013). This need is striking for, as but one example, older adults, for whom ankle moment FCU values during walking regularly exceed their plausible limits (i.e., >100%). Here, we found ankle moment FCU values during normal walking in young adults derived from dynamometry (i.e., 115%) were higher on average than those found previously (i.e., 85-93%) (Anderson & Madigan, 2014; Beijersbergen et al., 2013). Our isometric testing was performed using an ankle angle of 0°, approximating that at the instant of peak ankle moment and power generation in walking. This methodological decision may explain differences from prior work, which were performed at 26° dorsiflexion (Anderson & Madigan, 2014) or using a concentric action at 15 °/s (Beijersbergen et al., 2013) – the former likely conveying increased muscle force-generating capacity. Nevertheless, despite this methodological decision and consistent with our second hypothesis, the more functional "maximum" assessments of FCU conducted here during walking yielded smaller ankle moment FCU values (i.e., 76-78%) than others reported in the literature using dynamometry, especially compared to what we report for maximum speed walking (i.e., 152%). Consistent with ideas of Beijerbergen et al. (2013), we posit that plantarflexor muscle dynamics during dynamometry may predispose to ankle moment FCU calculations that fail to accurately reflect those during walking. For example, the plantarflexor muscles may tend to operate eccentrically during the stance phase of walking (Ishikawa, Komi, Grey, Lepola, & Bruggemann, 2005), which could increase their force-generating capacity compared to purely isometric muscle actions.

Finally, we cannot accept our third hypothesis that hip mechanical output would increase more in response to completing a ramped impeding force protocol than during maximum speed walking. Despite walking slower, hip extensor power during early stance was higher and its duration longer for the impeding force ramp protocol than for maximum speed walking, likely reflecting a disproportionate concentric demand on hip extensor muscles. However, the opposite was true for hip flexor power during late stance. Nevertheless, our data do show that young adults tap into extraordinarily large reserves available to muscles spanning the hip when increasing propulsive force generation during a ramped impeding force protocol. Most prominently, we discovered that young subjects walking at their preferred speed retain a reserve capacity to generate hip extensor moments of 53% and power of 83% during early stance. This was important for us to characterize because aging and many gait pathologies are associated with a well-documented redistribution of the mechanical demands of each step from the plantarflexor muscles to the hip extensor and/or flexor muscles (Cofre, Lythgo, Morgan, & Galea, 2011; DeVita & Hortobagyi, 2000; Franz, 2016; Judge et al., 1996; Kerrigan et al., 1998). Our findings are not altogether surprising; while not biomechanically equivalent, our ramped impeding force paradigm bears resemblance to a progressive ramped incline task. Compared to level walking, the hip extensor muscles of young and older adults undergo far larger increases in mechanical output than other muscle groups in response to walking uphill (Franz & Kram, 2014; Lay et al., 2006). Additional evidence during level walking shows that the relatively larger hip extensor muscles operate much further from their maximum isometric capacity than extensor muscles spanning the ankle (Anderson & Madigan, 2014; Beijersbergen et al., 2013). However, young adults instinctively rely much less on proximal leg joints than their older counterparts. This makes it challenging to predict how older adults will regulate leg muscle function to augment their propulsive forces in response to a similar impeding force protocol.

There are several limitations of this study. First, subjects' maximum overground walking speed surpassed previously reported values for the walk-to-run transition speed in young adults (~2 m/s) (Thorstensson & Roberthson, 1987). Plantarflexor muscle behavior, and presumably muscle force and/or power generation, systematically differs at speeds faster that the walk-to-run transition (Neptune et al., 2009). Further, our selected marker set could not quantify forward trunk lean, and thus we are unable to report precisely how much subjects used this strategy to enhance propulsive force generation in response to impeding forces. Instead, we relied on our instructions to the subjects not to adopt excessive forward lean, which we confirmed by visual inspection. The short duration of our maximum ramp condition (<30 s) was designed to allow subjects to reach their biomechanical maximum without reaching their metabolic maximum. However, we did not record metabolic cost and cannot comment on the potential effect of fatigue on our outcome measures. Additionally, to reduce fatigue effects, we assessed Ramp and Fast trials once per subject and strategically analyzed the single stride per trial associated with the largest anterior GRF. In our supplementary material, we report representative data from all strides taken during the Fast condition compared to the stride extracted and reported. However, motivated by the promising findings in this study, future work should aim to assess intra- and inter-session repeatability for these assessments to provide improved context for our conclusions. Finally, we selected the order of trials to minimize the influence of impeding forces on the Pref trial and to ensure the integrity of the maximum exertion during the Ramp trial. Although strategically designed, we cannot exclude the possibility of an ordering effect due to carry-over between conditions that may have influenced our outcome measures.

CONCLUSION

In closing, we used horizontal impeding forces to quantify the functional utilization of propulsive capacity during human walking - an approach that may have implications for the personalized prescription of interventions for individuals with walking ability limitations exemplified by reduced push-off intensity. For example, such information would enable the more discriminate prescription of conventional intervention (i.e., resistance training) to those individuals with insufficient propulsive reserves. In contrast, individuals with sizeable but underutilized propulsive reserves during walking may respond best to interventions designed to encourage access to those reserves, for example through the use of biofeedback (Franz et al., 2014; Schenck & Kesar, 2017). The reference young adult data reported here provide an important benchmark for future translational work and, thereafter, clinical decision making in gait rehabilitation.

CHAPTER 3: INCREASING THE PROPULSIVE DEMANDS OF WALKING TO THEIR MAXIMUM ELUCIDATES FUNCTIONALLY LIMITING IMPAIRMENTS IN OLDER ADULT GAIT[2]

INTRODUCTION

Age-related mobility impairment and reduced independence arise in part from the shorter steps and slower preferred speeds (Beijersbergen et al., 2013). These changes likely arise from deficits in push-off intensity; compared to young adults, older adults walk with smaller peak propulsive ground reaction forces (GRF), diminished ankle joint kinetics, and reduced trailing limb extension (Cofre et al., 2011; DeVita & Hortobagyi, 2000; Franz, 2016; Graf, Judge, Ounpuu, & Thelen, 2005; Kerrigan et al., 1998; Winter et al., 1990). Moreover, these determinants of push-off intensity are highly coordinated during walking, potentially obstructing our understanding of functional limitations in older adult gait. For example, diminished ankle joint kinetics (i.e., moment, power, and work) may reduce propulsive GRFs, while less trailing limb extension can have the same effect while reorienting the GRF vector. However, despite biomechanical deficits compared to young adults walking at the same speed, many older adults retain the capacity to enhance push-off intensity in their community, for example to walk faster (Graf et al., 2005; Kerrigan, Lee, Collins, Riley, & Lipsitz, 2001; Kerrigan et al., 1998) or uphill (Franz & Kram,

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[2] This chapter previously appeared as an article in the *Journal of Aging and Physical Activity*. The original citation is as follows: Conway, K. A., & Franz, J. R. (2019). Increasing the Propulsive Demands of Walking to their Maximum Elucidates Functionally Limiting Impairments in Older Adult Gait. *J Aging Phys Act*, 1-28. doi:10.1123/japa.2018-0327

2013a, 2013b, 2014). Accordingly, it remains unclear which determinants of push-off intensity represent genuine functionally limiting impairments in older adult gait versus biomechanical changes that do not directly limit walking performance.

Historically, increasing the propulsive demands of walking has been used to elucidate functional limitations in older adult gait – i.e., determinants of walking performance that older adults are incapable of increasing. For example, unlike young adults, Franz and Kram (2014) showed that older adults failed to increase peak ankle moment to walk uphill at 9° compared to level walking. In contrast, despite presenting with age-related deficits during level walking, those same older subjects increased peak propulsive forces, positive ankle work, and plantarflexor activation similar to younger subjects. However, because that study was performed at fixed speed and uphill slope, it is unclear whether older adults could have otherwise increased their peak ankle moment. In addition, even with invariant ankle joint kinetics, greater trailing limb extension can independently augment propulsive forces (Hsiao et al., 2015). Indeed, previous work (Kerrigan et al., 2001) implicated both smaller peak ankle power output and reduced trailing leg hip extension as functionally limiting impairments in older adult gait; only those age-related deficits persisted when subjects walked at a speed faster than preferred. However, subjects in that study were simply instructed to "walk fast", which likely yielded submaximal walking speeds. Thus, it remains inconclusive which age-associated deficits in push-off intensity during walking older adults are unable to overcome – critical information for the prescription of effective interventions.

We posit that by increasing the propulsive demands of walking to their maximum we can elucidate functional limitations in older adult gait. The conventional alternative is dynamometry, which assesses age-related deficits at the individual muscle level. Unfortunately, when applied to muscles most involved in regulating push-off intensity (i.e., plantarflexors), dynamometry yields maximum ankle moments that are easily exceeded even during normal walking. Is there a way to increase the propulsive demands of walking to their maximum when walking at one's preferred speed? Several authors (Danion et al., 1997; Farris, 2016; Gottschall & Kram, 2003, 2005; Na, Kim, & Lee, 2015) have used submaximal impeding forces during treadmill walking to understand the biomechanics of push-off during walking. Inspired by these studies, we recently showed that a maximum impeding force protocol required, on average, a 49% larger peak propulsive GRF, 50% more hip extension, 22% larger peak ankle moment, and 43% larger peak ankle power in young adults walking at their preferred speed (Conway et al., 2018). However, no study to our knowledge has used horizontal impeding forces to quantify constraints on push-off intensity in older adults.

We used maximum speed walking and a custom impeding force system to increase the propulsive demands of walking to their maximum while elucidating functionally limiting impairments in older adult gait compared to reference data in young adults. We also sought to evaluate the extent to which older adults retain the capacity to enhance metrics of push-off intensity, information that could be leveraged to inform the prescription of gait interventions. We first hypothesized that older adults would walk normally with diminished push-off intensity compared to young adults, evidenced by reduced trailing limb extension, peak propulsive GRF, ankle joint kinetics, and positive CoM work during push-off. Second, we hypothesized that older adults overcome these deficits when the propulsive demands of walking are increased to their maximum. Accordingly, we would interpret age-related differences that endured across experimental manipulations as functionally limiting factors in older adult gait. Finally, we assessed the utility of dynamometry in assessing ankle moment generating capacity in walking. We hypothesized that dynamometry would underestimate peak ankle moments available to older adults during walking.

METHODS

An a priori power analysis revealed that 10 subjects would have 80% power to detect ($p<0.05$) both a 3%BW deficit in propulsive GRF and a 26% deficit in ankle power in old versus young subjects (Browne & Franz, 2017). Thus, 12 healthy older (age: 75.0±4.6 years, height: 1.71±0.1 m, mass: 68.6±11.1 kg) and 12 healthy young adults (age: 24.3±5.4 years, height: 1.84±0.2 m, mass: 70.5±7.6 kg) participated, excluded based on cardiopulmonary/neurological impairment and/or current musculoskeletal injury. On average, our older adult subjects performed vigorous activity 3.6 ± 2.0 times a week, moderate activity 4.2 ± 1.4 times a week, and light activity 4.5 ± 2.1 times a week and reported a falls efficacy score of 10.1 ± 0.3**,** out of a possible 100, with 10 being the score least associated with fear of falling. Subjects provided written informed consent as per the UNC IRB's ethical approval.

We determined older adults' preferred and maximum overground speeds, using a wireless photo cell timing system (Brower, UT), as the average of three times each taken to walk the middle 2m of a 10m walkway. Subjects completed walking trials on a dual-belt, force-measuring treadmill (Bertec, Corp. Columbus, OH). After 5 min acclimation, older subjects walked normally at their preferred speed for 1 minute ("Pref"). We then connected subjects' waist belt to a custom, feedback-controlled impeding force system, described in more detail previously (**Fig. 8**) (Conway et al., 2018). The motor (Kollmorgen, Radford, VA) was controlled by a real-time LabVIEW interface and motor controller (National Instruments, Austin, TX) according to instantaneous load cell feedback. This system progressively increased the propulsive demands of walking to maximum using horizontal impeding forces increasing at the rate of 1%BW/s ("Ramp", **Fig. 8**). Following our instructions, subjects completed the task while avoiding forward trunk lean and maintaining their position on the treadmill. The trial ended following an inexorable 0.35 m posterior displacement of the subject's waist belt, corresponding to approximately half the treadmill length, monitored using LabVIEW. This criterion essentially established when subjects were physically incapable of continuing to maintain their walking speed on the treadmill. All subjects completed one practice ramped impeding force trial to introduce them to the condition and confirm the displacement limit. After a 5-minute rest, subjects completed the Ramp condition with verbal encouragement to walk for as long as possible. Finally, starting from rest, we accelerated the treadmill at a constant rate of 0.2 m/s^2 until reaching subjects' maximum overground speed ("Fast") without impeding forces, maintained for approximately 5 seconds. Breaks between trials were provided as needed, and we note that subjects performed the fast walking condition in the absence of impeding forces.

We recorded trajectories of 31 retroreflective markers (100 Hz) on the pelvis and legs using a 14-camera motion capture system (Motion Analysis, Corp., Santa Rosa, CA) in synchrony with 3D GRF data recorded at 1000 Hz. Data were filtered using 4^{th} order low-pass Butterworth filters with cutoff frequencies of 6 Hz and 100 Hz, respectively. We used a standing trial and functional hip joint centers from right and left leg circumduction tasks (Piazza et al., 2001) to scale a seven segment, 18 degree-of-freedom lower extremity model (Arnold et al., 2010). These models and an inverse dynamics routine described in detail previously (Silder et al., 2008) estimated leg joint kinematics and kinetics. Trailing limb angle was calculated as described previously (Hsiao et al., 2015). We also time-integrated the ankle joint power curves to calculate positive ankle work during push-off (i.e., trailing leg double support). Finally, to further quantify push-off intensity at the limb level, we used the individual limbs method (ILM) to calculate mechanical work performed on the body's center of mass, specifically that performed by the trailing limb during double support (Donelan, Kram, & Kuo, 2002). Here, we calculated the dot product of CoM velocity and the individual limb GRF to find instantaneous CoM power, and time-integrated those curves.

Finally, subjects performed isolated plantarflexor contractions while seated in a dynamometer (Biodex Medical Systems, Shirley, NY). We quantified subjects' maximum voluntary isometric ankle moment at five ankle angles spanning 10° dorsiflexion to 30° plantarflexion at ~20° knee flexion, replicating that near the push-off phase of walking. Subjects performed two, 4-second ramped contractions separated by 1-minute rest. Subjects also performed two concentric isokinetic (30 °/s) contractions spanning the same range of motion, separated by 1-minute rest. We calculated maximum isometric and isokinetic ankle moments as the peak value averaged across two repetitions.

For Pref, we time-normalized all outcome measures and analyzed the bilateral average. For Ramp and Fast, we analyzed the stride associated with the largest peak propulsive GRF. Our supplementary data (**Supplementary Figure 1**) compares this stride extracted for analysis to outcomes from the 2 strides before and 1 after the stride to provide additional context. Independent samples t-tests assessed the effects of age on each outcome during normal walking. A repeated-measures analysis of variance (rmANOVA) then tested for significant main effects of condition (Pref, Ramp, Fast) in older subjects. A second rmANOVA tested for significant differences between peak ankle moment exerted during isolated contractions (isometric and isotonic) and that extracted from treadmill walking (i.e., Pref, Ramp, Fast). For significant main effects, post-hoc pairwise comparisons identified differences between conditions using an alpha level of 0.05.

RESULTS

Age-related Difference During Normal Walking

Young and older subjects preferred similar walking speeds (young: 1.36±0.15 m/s, old: 1.28±0.16 m/s, $p=0.975$). However, compared to young adults, older adults walked with 14% smaller propulsive GRF ($p=0.012$, **Fig. 9**) and 27% less positive trailing leg CoM work ($p<0.001$, **Fig. 10**). Older adults also walked with 13% smaller peak ankle moments ($p=0.001$), 20% smaller peak ankle power ($p=0.017$), and 73% less peak hip extension than young adults ($p<0.001$) (**Figs. 11-12**).

Limb-level Outcomes

Compared to Pref, older adults increased peak propulsive force by 43% (24.7±4.1%BW vs. 17.3±2.5%BW, $p<0.001$) and 71% (29.6±3.7%BW vs. 17.3±2.6%BW, $p<0.001$) to walk at their maximum speed (i.e., Fast, 1.89±0.16 m/s) and when impeding forces were increased to their maximum (i.e., Ramp), respectively (**Fig. 9**). Older adults also increased trailing limb extension (Fast: 20.3±2.8° vs. 16.7±1.5°, $p<0.001$; Ramp: 23.5±3.5° vs. 16.7±1.5°, $p<0.001$) and positive trailing leg CoM work during push-off (Fast: 0.22±0.08 J/kg/step vs. 0.17±0.03 J/kg/step, $p=0.009$; Ramp: 0.28±0.08 J/kg/step vs. 0.17±0.03 J/kg/step, $p=0.001$, **Fig. 10**).

Joint-level Outcomes

Older adults increased peak hip extension and peak ankle moment, power, and positive work by an average of 133% (-8.5±8.5° vs. -2.8±6.8°, $p<0.001$), 11% (1.4±0.3 Nm/kg vs. 1.5±0.2 Nm/kg, $p<0.004$), 50% (4.6±1.0 W/kg vs. 3.1±0.6 W/kg, $p<0.001$), and 65% (0.5±0.1 J/kg/step vs. 0.3±0.1 J/kg/step, $p<0.001$) respectively, to increase their walking speed to maximum (**Figs. 11-12**). Of these outcomes, only peak ankle moment remained significantly smaller than young adults' walking at their preferred speed. Older adults also did not increase peak ankle moment for

Ramp versus Pref ($p=0.143$). In contrast, compared to Pref, older adults walked with 92% greater peak hip extension ($-7.0\pm6.6°$ vs. $-2.8\pm6.8°$, $p<0.001$), 20% larger peak ankle power (3.7 ± 1.0 W/kg vs. 3.1 ± 0.6 W/kg, $p=0.041$), and 78% more positive ankle work (0.5 ± 0.1 J/kg/step vs. 0.3 ± 0.1 J/kg/step, $p<0.001$) during Ramp.

Dynamometry

Peak isometric and isokinetic ankle moments were significantly smaller than those found during walking (versus Pref, p-values≤0.004, **Table 1**). At best, dynamometry assessments averaged 24% smaller than that during Pref ($p=0.004$) and 38% smaller than that during Fast ($p<0.001$) (i.e., isometric at 10° dorsiflexion).

Secondary Outcomes

Compared to Pref, older adults increased peak hip extensor moments during early stance by 86% (1.4 ± 0.5 Nm/kg vs. 0.9 ± 0.2 Nm/kg, $p=0.002$) and 67% (1.3 ± 0.4 Nm/kg vs. 0.9 ± 0.2 Nm/kg, $p=0.012$) for Fast and Ramp, respectively (**Fig. 13**). These changes were accompanied by, on average, 109% (1.9 ± 0.9 W/kg vs. 1.1 ± 0.4 W/kg, $p=0.011$) and 233% (3.0 ± 1.0 W/kg vs. 1.1 ± 0.4 W/kg, $p<0.001$) greater hip extensor power during early stance for Fast and Ramp, respectively. Also compared to Pref, older adults increased terminal stance peak hip flexor moments by an average of 87% (1.0 ± 0.3 Nm/kg vs. 0.6 ± 0.1 Nm/kg, $p<0.001$) and 34% (0.7 ± 0.2 Nm/kg vs. 0.6 ± 0.1 Nm/kg, $p=0.029$) and peak hip flexor power by an average of 128% (3.7 ± 1.0 W/kg vs. 1.7 ± 0.4 W/kg, $p<0.001$) and 66% (2.7 ± 0.7 W/kg vs. 1.7 ± 0.4 W/kg, $p=0.001$) for Fast and Ramp, respectively. Knee joint kinetic changes were more modest, but included increased extensor moments ($p=0.020$) and power absorption ($p=0.025$) for Fast versus Pref (**Fig. 13**).

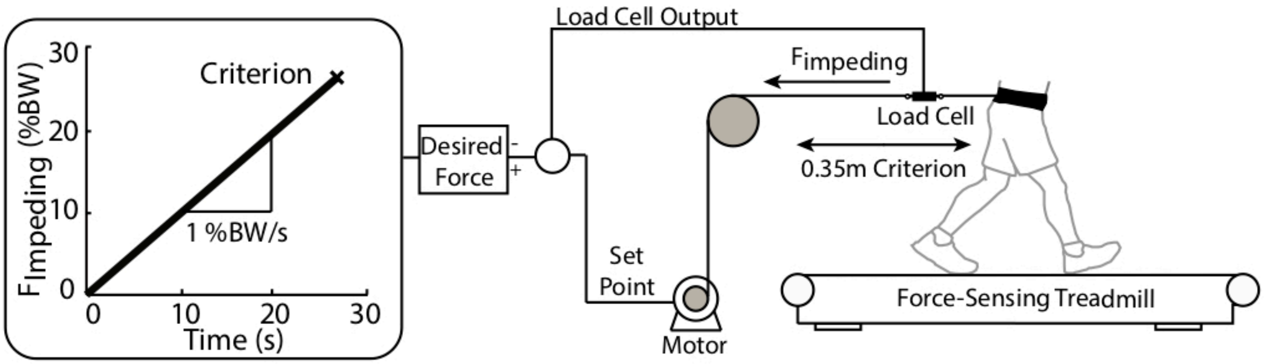


Figure 8: Schematic showing experimental approach to increasing the propulsive demands of walking. In the maximum impeding force trial, subjects wore a waist belt that connected horizontally via a stainless steel cable to a feedback controlled, motor-driven, impeding force system capable of prescribing horizontal impeding forces according to instantaneous measurements from a load cell. Specifically, we used a novel ramped impeding force protocol (Ramp) that increased at a rate of 1 %BW/s until the subjects reached the end point criterion, an inexorable 0.35 m posterior displacement of the subject's pelvis.

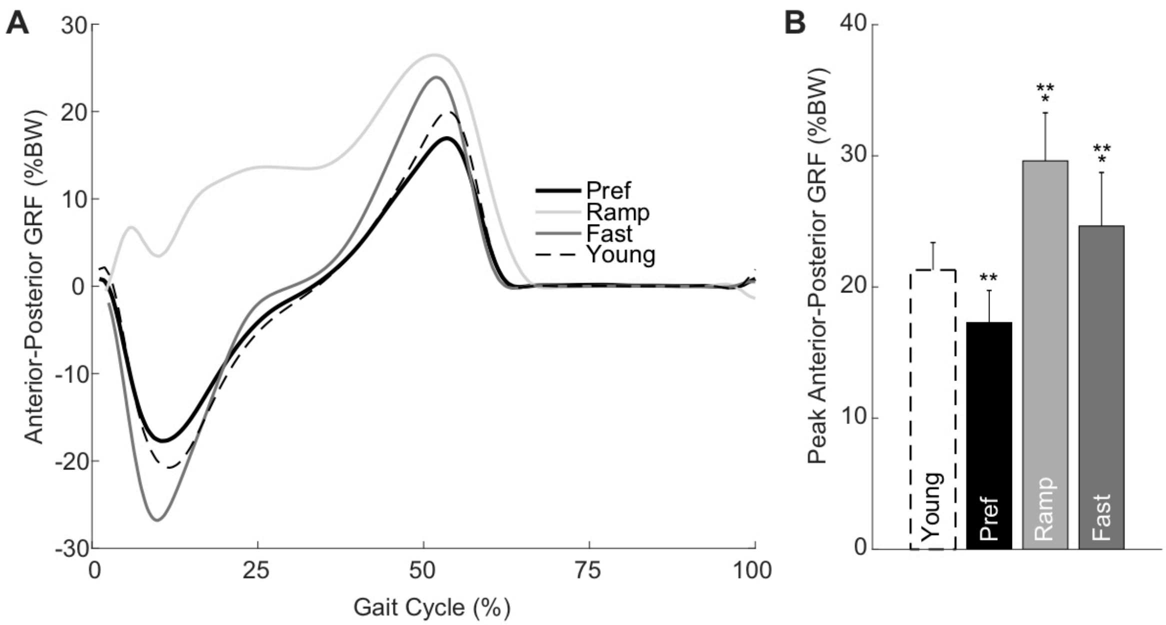


Figure 9: (A) Group average anterior-posterior ground reaction forces (GRF) for preferred (Pref), maximum ramp (Ramp) and maximum speed walking (Fast) compared to reference data in young adults whilst walking at preferred speed (Young) plotted against an average gait cycle, from heel-strike to heel-strike. **(B)** Group average (standard deviation) peak anterior ground reaction force during each condition. Single asterisks (*) represent local maxima with significant differences from Pref ($p<0.05$). Double asterisks (**) represent local maxima that are significantly different from Young ($p<0.05$).

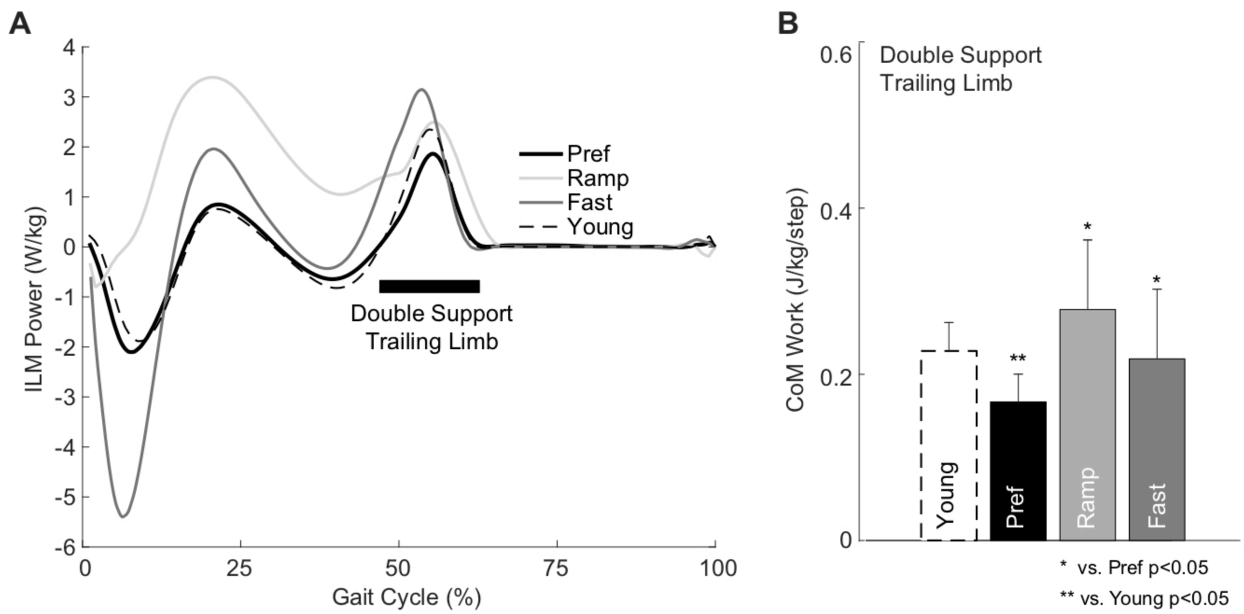


Figure 10: (A) Group average individual limb power for preferred (Pref), maximum ramp (Ramp) and maximum speed walking (Fast) compared to reference data in young adults walking at preferred speed (Young) plotted against an average gait cycle, from heel-strike to heel-strike. **(B)** Group average (standard deviation) center of mass work performed by the trailing leg during double support (indicated by the horizontal bar in panel A). Single asterisks (*) represent local maxima with significant differences from Pref (p<0.05). Double asterisks (**) represent local maxima that are significantly different from Young (p<0.05).

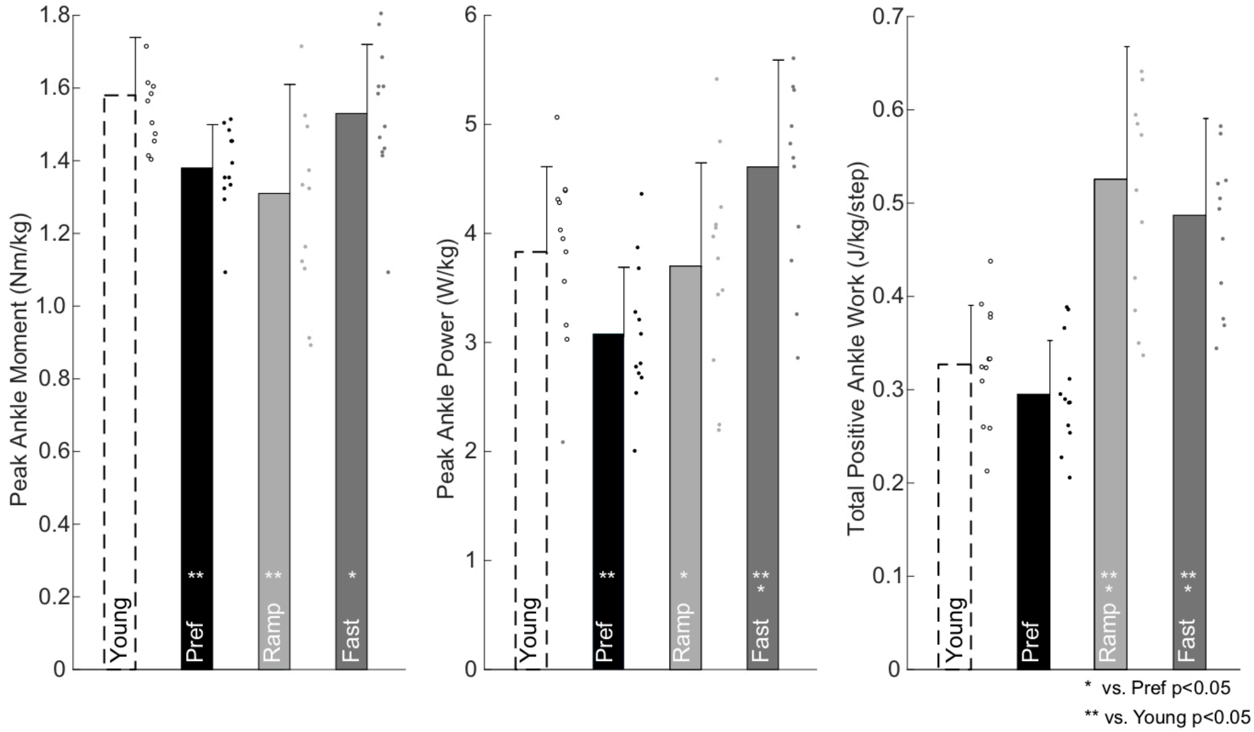


Figure 11: Group average (standard deviation) peak ankle moment, peak ankle power, and total positive ankle joint work for preferred (Pref), maximum ramp (Ramp), and maximum speed walking (Fast) compared to reference data in young adults walking at preferred speed (Young) plotted against an average gait cycle, from heel-strike to heel-strike. Dots on each plot represent individual subject data. Single asterisks (*) represent local maxima with significant differences from Pref (p<0.05). Double asterisks (**) represent local maxima that are significantly different from Young (p<0.05).

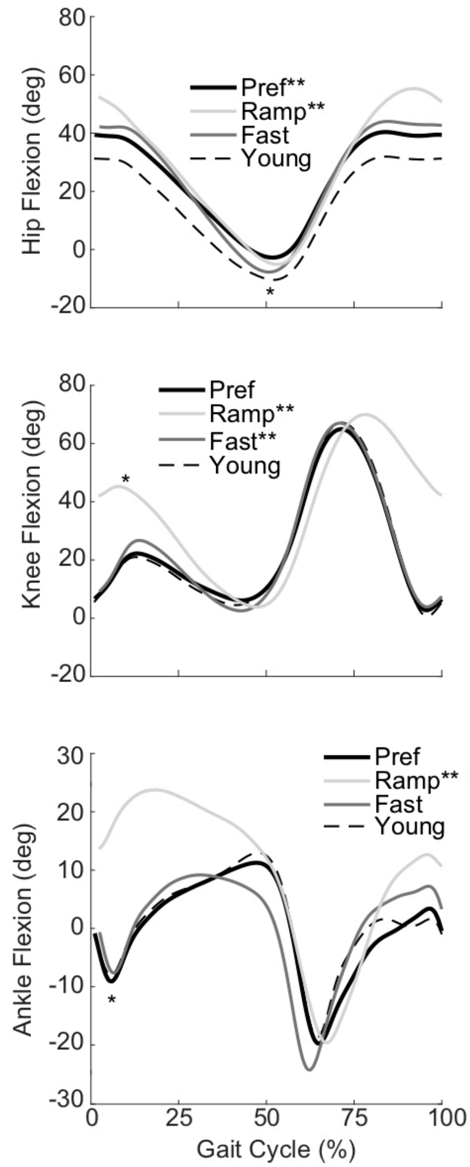


Figure 12: Group average hip, knee and ankle joint kinematics plotted against an averaged gait cycle, from heel-strike to heel-strike, for preferred (Pref), maximum ramp (Ramp) and maximum speed walking (Fast) trials compared to reference data in young adults walking at preferred speed (Young). Single asterisks (*) represent local maxima or minima with significant main effects of condition ($p<0.05$). Double asterisks (**) in the legend represent local maxima that were significantly different from Young ($p<0.05$).

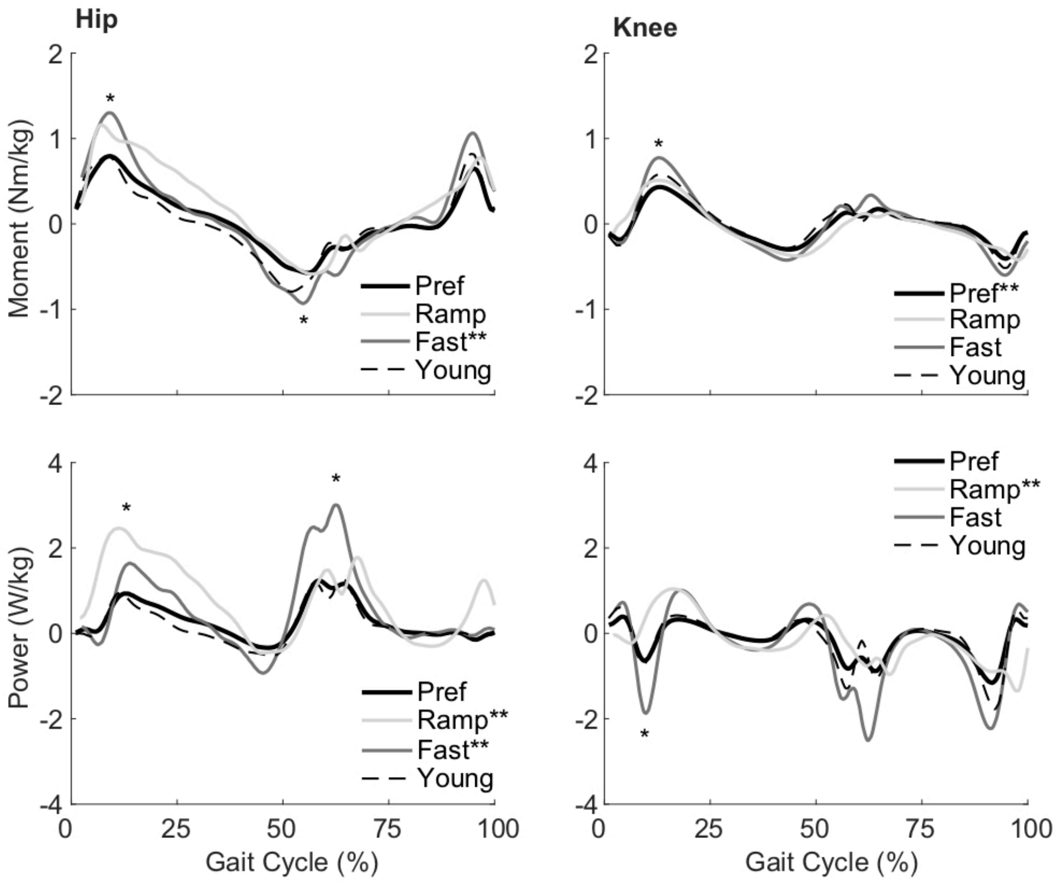


Figure 13: Group average hip and knee joint moments and powers plotted against an averaged gait cycle, from heel-strike to heel-strike, for preferred (Pref), maximum ramp (Ramp) and maximum speed walking (Fast) trials compared to reference data in young adults walking at preferred speed (Young). Positive values indicate internal extensor moment or power generation. Single asterisks (*) represent local maxima or minima with significant main effects of condition ($p<0.05$). Double asterisks (**) in the legend represent local maxima that were significantly different from Young ($p<0.05$). For the hip joint moment, this convention applied only to the hip extensor moment; hip flexor moment during Fast did not significantly differ from Young.

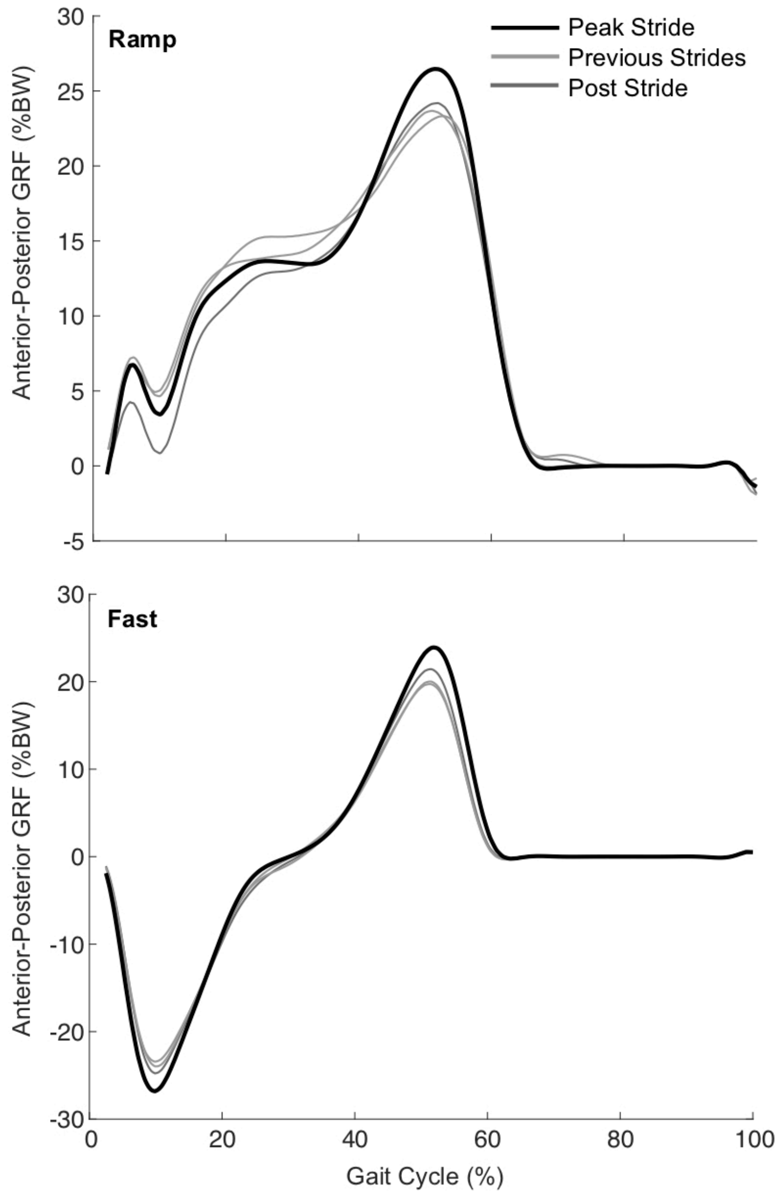
Table 1

Group mean ± standard deviation peak net ankle moment (Nm/kg)

Isometric					Isokinetic
-10°	0°	10°	20°	30°	30°/sec
1.11 ± 0.26*	0.92 ± 0.18*	0.67 ± 0.14*	0.52 ± 0.11*	0.33 ± 0.11*	0.67 ± 0.21*

Positive angles for isometric testing indicate plantarflexion.

Asterisks (*) Indicate significant difference from Pref walking condition peak net ankle moment (1.38 ± 0.12, $p<0.05$)



Supplementary Figure 1: Group average anterior-posterior ground reaction forces (GRF) for maximum ramp (Ramp) and maximum speed walking (Fast) conditions. Lines represent the peak stride extracted for analysis (i.e., that associated with the peak anterior force, black), compared to two strides before and one stride after (gray) plotted against an average gait cycle, from heel-strike to heel-strike.

DISCUSSION

We sought to elucidate functionally limiting impairments in older adult gait compared to reference data in young adults using a novel combination of maximum speed walking and horizontal impeding forces to increase the propulsive demands of walking to their maximum. In support of our first hypothesis, older adults exhibited hallmark deficits in limb- and joint-level determinants of push-off intensity compared to young adults. These findings are fully consistent with the prevailing literature (Cofre et al., 2011; DeVita & Hortobagyi, 2000; Franz, 2016; Kerrigan et al., 1998; Winter et al., 1990). However, in support of our second hypothesis, older adults retained a significant capacity to enhance push-off intensity while overcoming age-related deficits in propulsive GRF, trailing leg positive CoM work, peak trailing leg and hip joint extension, and ankle power generation. Those determinants of push-off intensity may be best described as changes that simply present as age-related deficits in walking performance. In contrast, among the biomechanical outcomes tested, our results implicate smaller peak ankle moments during push-off alone as functionally limiting in older adult gait.

Older adults almost universally exhibit diminished push-off intensity compared to young adults walking at the same speed (DeVita & Hortobagyi, 2000; Franz, 2016; Kerrigan et al., 1998; Winter et al., 1990). Moreover, diminished push-off is implicated as an early sign of future functional declines, for example precipitating shorter steps and slower speeds. However, the majority of studies reporting evidence for functional limitations do so based on differences between young and older adults during habitual speed walking. Our older subjects presented with propulsive deficits considered hallmark of older adult gait. Moreover, despite similar preferred speeds, our older subjects achieved slower maximum speeds than those we previously found for young subjects (i.e., 2.5±0.3 m/s (Conway et al., 2018)). Accordingly, we would consider them representative of older adults in the community and those participating in earlier studies. However, locomotor patterns adopted at preferred speeds are unlikely to reflect genuine age-related constraints on walking performance, particularly those thought to restrict push-off intensity (e.g., sarcopenia, muscle weakness, hip flexion contracture (Baumgartner et al., 1998; Kerrigan et al., 1998)).

Despite naturally emergent differences compared to young adults walking at the same speed, we suggest that age-related deficits in propulsive GRF, trailing limb and peak hip joint extension, ankle power generation, and positive ankle work merely masquerade as functionally limiting in otherwise healthy older adults. It is possible that these adaptations may be purposeful strategies to accommodate age-related changes in sensory acuity and/or balance integrity. Although we cannot exclude potential influence of sensory acuity, our recent evidence suggests that a reduced push-off intensity in older adults is likely unrelated to poor balance control (Browne & Franz, 2017). In either event, based on previous literature, it would be fully intuitive to interpret age-related deficits in these outcome measures during walking as functionally limiting, given their role in shaping walking performance. However, indirect but accumulating evidence against this conclusion demonstrated that older adults retain the ability to, for example, walk uphill or walk faster (Franz & Kram, 2013a, 2013b, 2014; Graf et al., 2005; Kerrigan et al., 1998). Interestingly, our older adult subjects increased their propulsive GRF by up to 71% when impeding forces were increased to their maximum, which is strikingly similar to that found previously (69%) when older adults walked 9° uphill (Franz & Kram, 2014). Together, we propose a possible ceiling effect in propulsive GRF resulting in an environmental barrier to community independence for older adults.

Ankle joint moment and trailing limb extension are both determinants of propulsive GRF during walking (Hsiao et al., 2015). Given the relatively invariant ankle moment across conditions, augmenting trailing limb extension may explain how subjects increased their propulsive GRF. This was accompanied by a delay in knee flexion and ankle extension during push-off, which alludes to an increase in relative stance duration, perhaps to prolong force generation prior to toe off in order to accommodate greater propulsive demands. These outcomes are particularly interesting, as the prevalence of hip flexion contracture in the aging population has led to clinical trials targeting reduced peak hip extension (Watt et al., 2011a, 2011b). However, despite increases in passive hip extension range, most older adults in those studies did not increase hip extension during walking. This suggests that habitual locomotor patterns in older adult gait are ingrained, perhaps alluding to a control issue that allows certain deficits to masquerade as functionally limiting even after intervention (Selinger, O'Connor, Wong, & Donelan, 2015) .

Conversely, older adults were unable to overcome age-related deficits in peak ankle moment during push-off, even when walking speed or impeding forces were increased to their maximum. Despite modest increases in peak ankle moment during maximum speed walking, older adults failed to exceed that generated normally by young adults, unique among our metrics of push-off intensity. This also appears exclusive to older adults; we previously showed that young adults increased peak ankle moment during maximum speed walking, on average, 3 times more than observed here in older adults (Conway et al., 2018). Similarly, older adults previously failed to increase peak ankle moment during uphill walking, unlike their younger counterparts (Franz & Kram, 2014). We would thus interpret ankle moment to be genuinely limiting of push-off intensity and thereby walking performance in the elderly. Peak ankle moment during push-off represents the product of plantarflexor muscle forces and their respective muscle-tendon moment arms. Indeed, many studies have implicated sarcopenia and leg muscle weakness as explanations for age-related deficits in walking performance. However, interventions to enhance strength, while reporting gains in force production, generally fail to improve self-selected gait performance (Beijersbergen et al., 2017). Thus, our understanding of age-related deficits in peak ankle moment generation is perhaps more limited than previously appreciated. As one example, the moment arm of the shared Achilles tendon exhibits unfavorable changes due to aging and correlates with reduced ankle moment in older adults (Rasske & Franz, 2018).

Unlike some age-related gait changes requiring sophisticated equipment, peak ankle moment may be quantified indirectly using dynamometry. For example, Silder et al. (2008) found that older subjects exerted 37% smaller concentric peak isokinetic ankle moments than young adults. Unfortunately, in support of our final hypothesis, isometric and isokinetic assessments of plantarflexor strength considerably underestimated peak ankle moments during walking for all conditions. That numerical values underestimate those in walking would not alone preclude the use of dynamometry for assessing age-related deficits in peak ankle moment. However, post-hoc testing revealed no significant correlations between isometric nor isokinetic measurements and ankle moment during Pref, Ramp, or Fast (p-values$\geq$0.209; r^2 values$\leq$0.15). We are not the first to report challenges in using dynamometry to assess plantarflexor muscle behavior during walking (Kahn & Williams, 2015; Milot et al., 2007). For example, Anderson and Madigan (2014) reported that doing so to understand functional utilization of peak ankle moment in older adults during walking yielded implausible values, exceeding 100% of that quantified during maximum isometric contractions. These discrepancies may arise from different muscle contractile dynamics, and thereby force-generating capacities, during walking compared to isolated contractions. Our ongoing ultrasound imaging work will explore this muscle-level explanation further. Nevertheless, we recommend against the use of dynamometry to assess age-related deficits in peak ankle moment generation in favor of more direct functional assessments made during walking.

Study Limitations

We did not quantify trunk lean in response to impeding forces. However, we instructed subjects to avoid excessive lean and confirmed this visually. Second, we selected the order of trials to prevent impeding forces from influencing preferred locomotor patterns and to ensure maximum exertion during Ramp. We cannot exclude the possibility of ordering effects. Similarly, Ramp duration (~20-30 seconds) was designed to prevent fatigue, however we cannot exclude those effects. In addition, our impeding force paradigm permitted small, but for our purposes negligible, vertical forces due to the natural rise and fall of the body's center of mass. We also analyzed only one trial per subject during the Fast and Ramp to avoid fatigue, strategically analyzing the stride with the largest propulsive GRF. While certain functional impairments disappear on short timescales such as those during the Ramp and Fast conditions, this may not be the case for longer durations. This study lays the groundwork for studying the persistence of such impairments over longer timescales. Finally, despite literature reporting the similarities in biomechanics during treadmill and overground walking, (Riley, Paolini, Della Croce, Paylo, & Kerrigan, 2007; Watt et al., 2010) we cannot be certain how use of the treadmill in our trials influenced the response to maximum speed walking and the impeding force Ramp condition.

CONCLUSION

Despite walking with hallmark age-related deficits in propulsive GRF, trailing limb positive CoM work, trailing leg and hip joint extension, and ankle power generation, older adults are capable of overcoming those deficits when the propulsive demands of walking are increased to their maximum. In contrast, older adults appear physically incapable of fully overcoming deficits in peak ankle moment during walking, alluding to a lone genuine functionally limiting impairment.

CHAPTER 4: SHORTER GASTROCNEMIUS FASCICLE LENGTHS IN OLDER ADULTS ASSOCIATE WITH WORSE CAPACITY TO ENHANCE PUSH-OFF INTENSITY IN WALKING[3]

INTRODUCTION

The plantarflexor muscles provide the majority of mechanical power needed for forward propulsion during the push-off phase of walking (Francis et al., 2013; Gottschall & Kram, 2003; Neptune et al., 2009). Accordingly, reduced push-off intensity during walking, arising from diminished plantarflexor mechanical output, is thought to play an important role in age-related mobility impairment (DeVita & Hortobagyi, 2000; Franz, 2016; Winter et al., 1990). We recently discovered that older adults perform significantly worse than young adults on tasks designed to increase the propulsive demands of walking to their maximum not simply during maximum speed walking, but also at preferred speed using a maximum ramped impeding force condition (Conway & Franz, 2019). We posit that an age-related shift toward shorter plantarflexor operating lengths, perhaps governed in part by increased tendon compliance, functionally limits force generation and thereby the ability of those muscles to respond to increased propulsive demands during walking. This study represents an initial but important step toward understanding the veracity of this overarching premise.

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[3] This chapter previously appeared as an article in the *Gait and Posture*. The original citation is as follows: Conway KA, Franz JR. (2020). Shorter gastrocnemius fascicle lengths in older adults associate with worse capacity to enhance push-off intensity in walking. *Gait Posture*. 2020;77:89–94. doi:10.1016/j.gaitpost.2020.01.018

Elderly gait is characterized by hallmark reductions in push-off intensity and thus forward propulsion. Specifically, older adults habitually walk with deficits in peak anterior ground reaction forces and ankle joint kinetics compared to young adults, which are considered relevant to reduced stride lengths and walking speed. (DeVita & Hortobagyi, 2000; Franz, 2016; Graf et al., 2005; Winter et al., 1990). The plantarflexor (i.e. gastrocnemius and soleus) muscles are mostly responsible for this forward propulsion provided during walking (Franz, 2016; Gottschall & Kram, 2003; McGowan, Neptune, & Kram, 2008). Growing evidence is beginning to implicate age-related changes in plantaflexor muscle length-tension behavior, independent of deficits in force-generating capacity, in governing walking performance (Mian, Thom, et al., 2007; Panizzolo et al., 2013; Stenroth et al., 2015).

Recent advances in ultrasound image analysis have enabled *in vivo* plantarflexor muscle fascicle tracking during functional activities such as walking (Cronin et al., 2011; Farris & Lichtwark, 2016; Farris & Sawicki, 2012). However, only a small number of previous studies directly compared the plantarflexor muscle operating behavior of both young and older adults during walking. At matched speeds, the soleus muscle fascicles of older adults are shorter across the gait cycle compared to their young counterparts, and undergo less relative shortening (Panizzolo et al., 2013). However, the contractile behavior of the uniarticular soleus muscle may differ from the biarticular gastrocnemius muscles, which potentially play a larger role in governing forward propulsion (Francis et al., 2013; Gottschall & Kram, 2003). Older adults gastrocnemius fascicles have also been found to remain shorter during the gait cycle compared to young adults (Mian, Thom, et al., 2007). However, how the medial gastrocnemius muscle accommodates increased propulsive demand at the fascicle level, and how this may change with age, is currently unknown.

Evidence that older adults' plantarflexor muscle fascicles operate at shorter lengths (Mian, Thom, et al., 2007; Panizzolo et al., 2013) alludes to the potential for deficits in force production per the force-length properties of muscle (Hill & White, 1968; Rassier et al., 1999). For example, if aging muscle fascicles are habitually operating further down the ascending limb, force generating capacity would be limited compared to young muscle fascicles for the same unit activation. Indeed, in older adults, resting fascicle lengths of the medial gastrocnemius have been correlated with functional walking performance measures such as the 6-minute walk test (Stenroth et al., 2015). Therefore, our overarching hypothesis is that older, shorter muscle fascicles would be less able to respond to increases in force (i.e. task) demands, with potential consequences in the community such as walking uphill, accelerating, and/or stair ascent.

In order to investigate whether plantarflexor muscle operating lengths are a limiting factor in aging gait, and to gain an improved muscle-level understanding of the mechanisms responsible for generating propulsion during walking, we increased the propulsive demands of walking to their maximum in young and older adults via maximum speed walking and a maximum impeding force protocol at preferred speed. We hypothesized that gastrocnemius muscle fascicle length at peak ankle moment during walking would be shorter in older than young adults. We also hypothesized that, independent of muscle strength, shorter fascicle lengths during normal walking would predict (i.e. correlate with) worse performance on tasks that increase the propulsive demands of walking to their maximum.

METHODS

9 healthy young (YA, age: 25.3±4.9 years, height: 1.71±0.1 m, body mass: 71.6±8.4 kg, 5M/4F) and 9 healthy older subjects (OA, age: 75.3±2.7 years, height: 1.72±0.1 m, mass:

71.2±10.9 kg, 5M/4F) participated. The protocol was approved by the UNC Biomedical Sciences Institutional Review Board and all subjects provided written informed consent before participating. Subjects had no neurological disorders or disease, had not suffered neurological or musculoskeletal injury in the previous 6 months, and could walk without an assistive device.

We first recorded subjects' preferred and maximum safe walking speeds as the average of three times taken to traverse the middle 2 m of a 10 m walkway. Subjects then walked on an instrumented dual belt treadmill (Bertec Corp., Columbus, OH) at their preferred walking speed for 5 min to pre-condition the plantarflexor muscle-tendon units (Hawkins, Lum, Gaydos, & Dunning, 2009) and allow their movement patterns to stabilize. Subjects then performed a series of ramped isometric voluntary contractions at a neutral (*i.e.*, 0°) ankle angle in a dynamometer (Biodex, Shirley, NY). The knee was flexed to ~20° to replicate that near the push-off phase of walking, while straps over the foot and thigh limited extraneous motion. We verbally encouraged subjects to reach their maximum effort for each of two, 4-second ramped contractions separated by at least one minute. We defined subjects' maximum isometric ankle moment as the peak generated during the isometric contraction, averaged across the two repetitions.

We then collected a normal, baseline trial while subjects walked at their preferred speed on the treadmill for 1 minute ("Pref"). After a 5-minute rest, we used a custom, feedback-controlled, motor-driven horizontal impeding force system (**Fig. 14**). The details of this system are described in detail elsewhere (Conway et al., 2018; Conway & Franz, 2019). Briefly, the system consists of a servo motor (Kollmorgen, Radford, VA) controlled in real-time using a LabVIEW interface (NI PCI 7352, National Instruments, Austin, TX) based upon instantaneous signals recorded from a load cell (Futek, Irvine, CA) in series with a cable connection to a waist belt worn by the subjects. Using this system while subjects walked at their preferred speed, we applied a horizontal impeding force that increased at a rate of 1 %BW/s ("Ramp"), thereby increasing the propulsive demands of walking to their maximum. Subjects were instructed to avoid excessive forward lean and to maintain their position on the treadmill until they could no longer sustain the impeding forces. Subjects received verbal encouragement to continue walking for as long as possible in the presence of the impeding forces. Similar to our earlier study (Conway & Franz, 2019), this Ramp trial ended after an inexorable 0.35 m displacement of the subjects' pelvis, monitored in real-time by the motor's encoder. Finally, subjects completed a walking trial on the treadmill which started from rest before increasing to their maximum safe overground walking speed ("Fast") at a constant rate of 0.2 m/s^2, which was sustained for at least 5 seconds for data collection.

For treadmill trials, 3D trajectories of 31 retroreflective markers recorded at 100 Hz on the pelvis and lower limbs were recorded using a 14-camera motion capture system (Motion Analysis Corp. Santa Rosa, CA) while 3D ground reaction force (GRF) data were simultaneously recorded at 1000 Hz. Data were then filtered using 4^{th} order low-pass Butterworth filters with cutoff frequencies of 6 Hz (marker data) and 100 Hz (GRF data). We used a standing trial and functional hip joint centers from right and left leg circumduction tasks (Piazza et al., 2001) to scale a seven segment, 18 degree-of-freedom model of the pelvis and lower limbs (Arnold et al., 2010). Finally, we used these scaled models and an inverse dynamics routine described in detail previously to estimate leg joint kinematics, muscle tendon unit (MTU) lengths, moments, and powers (Silder et al., 2008). For Pref, we averaged time-normalized right leg outcome measures across the 1-minute trial. For Ramp and Fast, we found the time-normalized right leg stride associated with the peak anterior ground reaction force and averaged this with the previous 3 strides.

During all trials, a 60 mm linear array ultrasound transducer (Echoblaster 128, 10 MHz, Telemed, Vilnius, Lithuania) was placed over the mid-belly of the right medial gastrocnemius which recorded B-mode images at 61 frames/s through an image depth of 65 mm. We used open source MATLAB routines (Farris & Lichtwark, 2016) based on an optic flow algorithm to analyze the cine B-mode images. Following previously outlined techniques (Cronin et al., 2011), the same investigator tracked all muscle data by first defining a region of interest surrounding each muscle and their aponeuroses before defining a gastrocnemius muscle fascicle in the mid-belly of the image from the superficial to deep aponeuroses. Manual corrections were made following visual inspection. These MATLAB routines then quantified time series of muscle fascicle lengths averaged across 3 strides, the derivative of which provided fascicle shortening velocity across the gait cycle or contraction. For the Ramp and Fast conditions, we analyzed strides during the last 5 seconds of each trial.

Our walking outcome measures were peak ankle moment, medial gastrocnemius fascicle length at peak ankle moment, peak fascicle length change, and muscle-tendon unit length change. Our secondary outcome measures were preferred and maximum walking speeds, performance on the impeding force Ramp condition, and isometric strength. For primary outcome measures, a repeated-measures analysis of variance (rmANOVA) tested for significant main effects of condition (Pref, Ramp, Fast) and age (young, older). For significant main effects, post-hoc pairwise comparisons identified the effects of age at each condition using an alpha level of 0.05. For secondary outcome measures, an independent samples t-test statistically compared older vs. young adults using the same alpha level. Finally, we calculated Pearson correlation coefficients between gastrocnemius fascicle measurements and performance on the Ramp (i.e., %BW) and Fast conditions (i.e. maximum speed).

RESULTS

Older and young adults walked overground at similar preferred speeds (YA: 1.32±0.16 m/s, OA: 1.28±0.13 m/s, $p=0.557$, $d=0.283$). However, older subjects reached a 25% slower maximum walking speed (YA: 2.51±0.29 m/s, OA: 1.89±0.17 m/s, $p<0.001$, $d=2.661$, **Fig. 16A**) than young subjects, and performed 35% worse on the Ramp condition ($p=0.036$, $d=1.081$, **Fig. 16C**). We also found no significant difference in average isometric strength ($p=0.125$, $d=0.762$) nor peak ankle moment during preferred speed walking between young and older adults ($p=0.744$, $d=0.121$, **Table 2**). However, a significant age×condition interaction ($p=0.003$, $\eta_p^2=0.514$) revealed that peak ankle moment was significantly lower in older adults for Ramp (-23%, $p=0.017$) and Fast (-20%, $p=0.010$).

During Pref, gastrocnemius fascicle lengths at peak ankle moment in older adults averaged 7% shorter than those in young, however this difference was not statistically significant ($p=0.189$, **Fig. 15A**). A significant main effect ($p=0.009$, $\eta_p^2=0.600$) revealed that gastrocnemius fascicle shortening relative to heel-strike was significantly diminished by age, and that this was exacerbated during the Fast (vs. YA, -43%, $p=0.017$) and Ramp (vs. YA, -65%, $p=0.001$) conditions relative to Pref (vs. YA, -29%, $p=0.092$) (**Fig. 15B**). This age-related reduction in peak shortening at the fascicle level was not explained by differences in MTU length (**Fig. 15C-D**). Significant main effects ($p=0.021$, $\eta_p^2=0.506$) revealed that peak gastrocnemius shortening velocity was significantly slower in older than young adults, especially during the Pref (vs. YA, -65%, $p<0.001$), and Ramp conditions (vs. YA, -53%, $p=0.028$, **Table 2, Supplementary Figure 2**). Similarly, a main effect ($p=0.005$, $\eta_p^2=0.644$) revealed slower peak shortening velocity at the instant of peak ankle moment for older adults, particularly during Fast (vs. YA, -72%, $p=0.004$) and Ramp conditions (vs. YA, -107%, $p=0.010$, **Table 2, Supplementary Figure 2**).

Across our study cohort, we found that gastrocnemius fascicle length at peak ankle moment during Pref exhibited a significant moderate correlation with performance on the Ramp condition ($p=0.020$, $r^2=0.293$, **Fig. 16B**). This relation was driven by that in older adults ($p=0.005$, $r^2=0.704$) and remained significant after controlling for isometric strength (OA: $p=0.011$, $r^2=0.792$) and subject height (OA: $p=0.010$, $r^2=0.700$). Conversely, we found no correlation between fascicle length at peak ankle moment during Pref and maximum speed (All: $p=0.134$, $r^2=0.135$. OA: $p=0.759$, $r^2=0.014$) or change to maximum speed (i.e. Fast-Pref, All: $p=0.096$, $r^2=0.164$. OA: $p=0.172$, $r^2=0.249$).

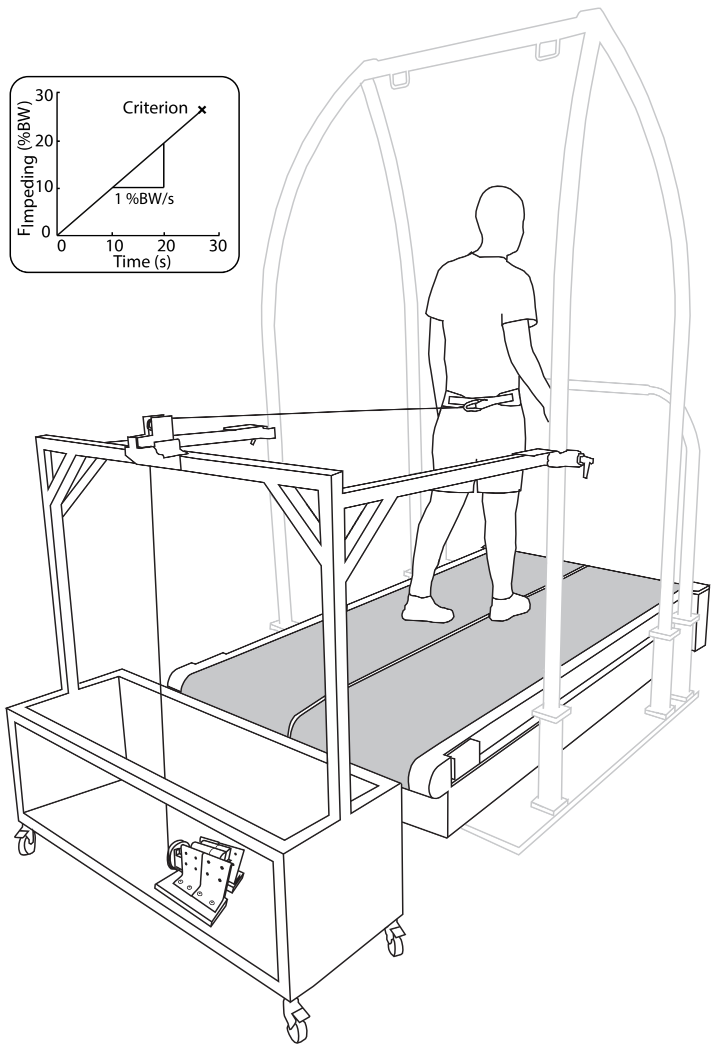


Figure 14: Schematic showing experimental approach to increasing the propulsive demands of walking. In the maximum impeding force trial, subjects wore a waist belt that connected horizontally via a stainless-steel cable to a feedback controlled, motor-driven, impeding force system capable of prescribing horizontal impeding forces according to instantaneous measurements from a load cell. Specifically, we used a novel ramped impeding force protocol (Ramp) that increased at a rate of 1 %BW/s until the subjects reached the end point criterion, an inexorable 0.35 m posterior displacement of the subject's pelvis.

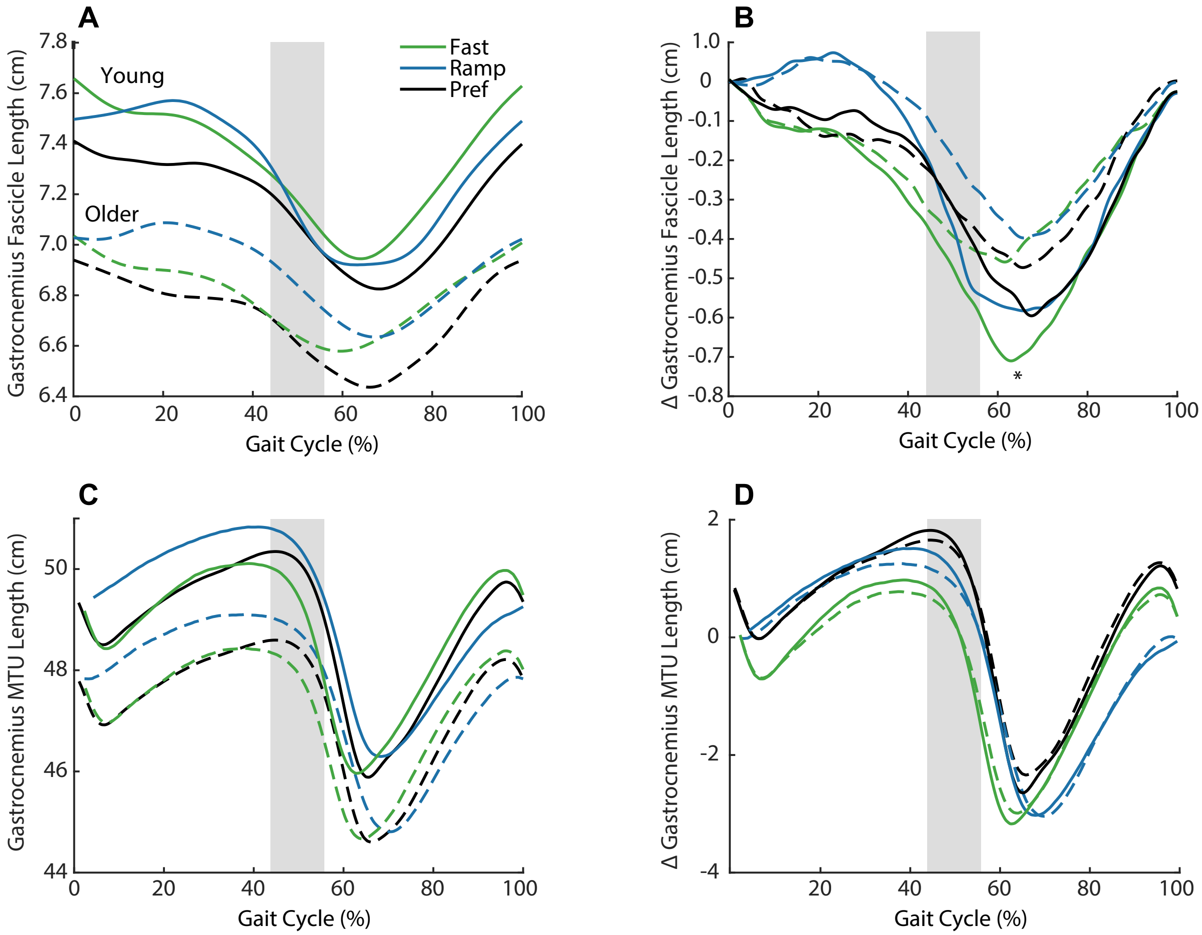


Figure 15: Muscle fascicle and muscle-tendon unit outcomes for preferred (Pref), maximum ramp (Ramp), and maximum speed walking (Fast) for both young (solid lines) and older adults (dashed lines), plotted against an average gait cycle, from heel-strike to heel-strike. Group average (A) absolute and (B) change (Δ) in medial gastrocnemius fascicle lengths. Group average (C) absolute and (D) change (Δ) in gastrocnemius muscle-tendon unit lengths. Shaded regions indicate the timing of peak ankle moment across our cohort. Single asterisks (*) represent local minima with significant age effect ($p<0.05$).

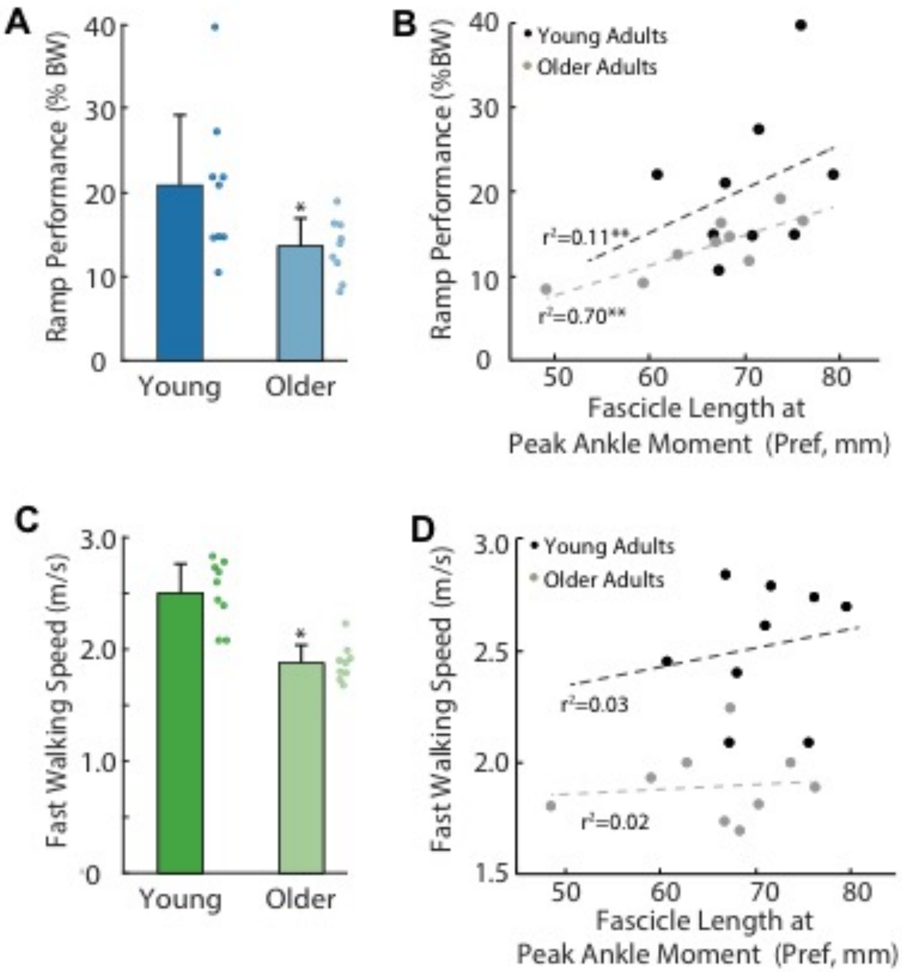
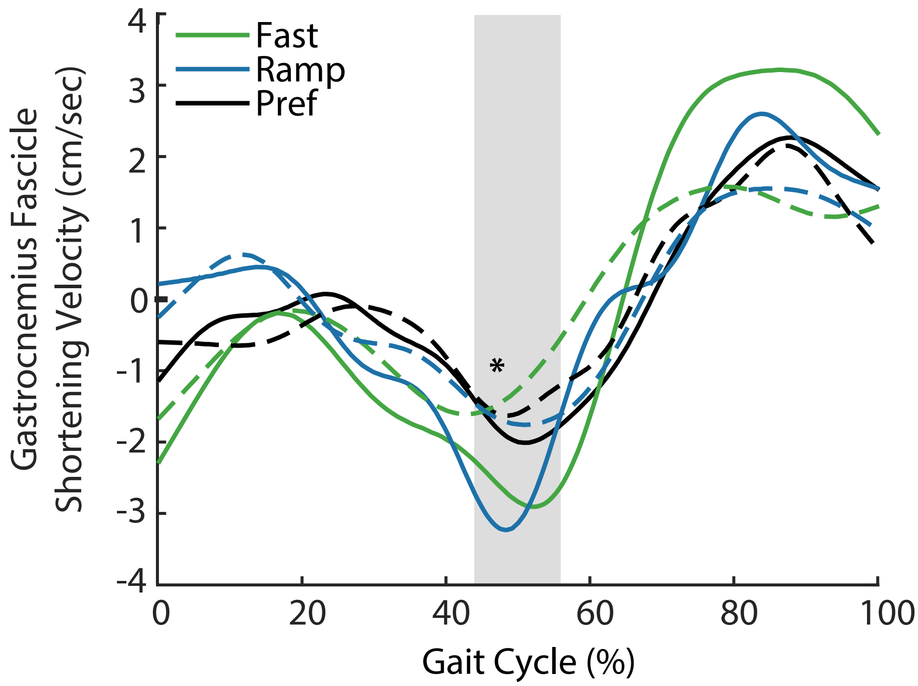


Figure 16: (A) Individual and group average (standard deviation) performance on the Ramp condition as percent bodyweight (% BW) for young and older adults. **(B)** Bivariate correlations between performance in the Ramp condition and gastrocnemius fascicle length at peak ankle moment from preferred walking for older (grey) and young (black) adults. **(C)** Individual and group average (standard deviation) maximum (i.e. Fast) walking speed for young and older adults. **(D)** Bivariate correlations between maximum (i.e. Fast) walking speed and gastrocnemius fascicle length at peak ankle moment from preferred walking for older (grey) and young (black) adults. Lines in B and D represent best-fit linear regressions. Single asterisks (*) represent a significant age effect ($p<0.05$). Double asterisks (**) represent a significant correlation ($p<0.05$).



Supplementary Figure 2: Group average medial gastrocnemius muscle fascicle velocity for preferred (Pref), maximum ramp (Ramp), and maximum speed (Fast) for both young (solid lines) and older adults (dashed lines), plotted against an average gait cycle, from heel-strike to heel-strike. Positive indicates fascicle lengthening. Shaded regions indicate the timing of peak ankle moment across our cohort. Single asterisks (*) represent local minima with significant age effect ($p<0.05$).

DISCUSSION

We investigated muscle-level mechanisms responsible for performance on walking tasks designed to increase the propulsive demands of walking to their maximum in older compared to young adults. Our findings did not support our first hypothesis; the tendency toward shorter medial gastrocnemius muscle fascicle lengths at peak ankle moment in older versus young adults was not statistically significant. However, in partial support of our second hypothesis, shorter medial gastrocnemius fascicle lengths during normal walking did correlate with worse performance on our maximum ramped impeding force protocol performed at subjects' preferred walking speed. This relationship was particularly dominant in older adults, even after controlling for plantarflexor muscle strength or subject stature. In contrast, independent of age, gastrocnemius fascicle lengths during habitual walking appeared unrelated to maximum walking speed.

Previous work has shown that older adults' fascicle lengths are generally shorter than their younger counterparts (Mian, Thom, et al., 2007; Panizzolo et al., 2013). Few studies have shown time-series medial gastrocnemius fascicle data during the gait cycle for older adults. However, our fascicle data are well-aligned with previously reported *in vivo* ultrasound imaging of the plantarflexors during walking (Cronin, Avela, Finni, & Peltonen, 2013; Cronin et al., 2011; Farris & Sawicki, 2012; Ishikawa et al., 2005; Lai et al., 2015; Mian, Thom, et al., 2007; Panizzolo et al., 2013; Rubenson, Pires, Loi, Pinniger, & Shannon, 2012). Our older adult cohort walked with reduced peak fascicle shortening during all conditions compared to young adults – an outcome not explained by reduced MTU shortening or ankle angle alone. Although the specific mechanisms driving this age effect are unclear, it would facilitate relatively longer fascicle lengths at slower shortening velocities during push-off and was disproportionately prevalent when the propulsive demands of walking were increased. Longer fascicle lengths at slower shortening velocities may convey a physiological advantage to muscle force generation when task demands are high, and deficits in muscle strength may precipitate the need for such changes. Consistent with this premise, older and young adults exhibited more pronounced fascicle lengthening during early to mid-stance in response to Ramp than during Pref. However, similar behavior was also observed for muscle-tendon unit length, suggesting that at least part of this change can be explained by changes in ankle and knee joint kinematics. Nevertheless, these findings suggest that gastrocnemius fascicle operating lengths are fundamentally altered by age and contribute to adaptation within the muscle-tendon unit complex in response to increased propulsive demands during walking.

Medial gastrocnemius fascicle lengths strongly correlated with performance in the ramped impeding force condition in older adults. This association was not prevalent in younger subjects and persisted even after controlling for isometric plantarflexor strength and subject stature. We interpret this finding to suggest that gastrocnemius operating behavior, independent of inter-individual differences in strength or anthropometrics, plays a mechanistic role in governing one's capacity to enhance push-off intensity during walking at a constant speed. We are certainly not the first to implicate age-related changes in plantarflexor muscle fascicle length-tension behavior in reduced performance in functional mobility tasks. Indeed, Stenroth et al. (2015) reported that medial gastrocnemius fascicle lengths in older adults, in addition to Achilles tendon stiffness, correlated with improved distance on the 6 minute walk test (Stenroth et al., 2015). Combined, these associations warrant further research into rehabilitation techniques that focus on ways to steer muscle contractile dynamics in those with diminished push-off intensity. For example, attempts to stiffening the Achilles tendon may have favorable implications for the corresponding plantarflexor muscle fascicle behavior. In addition to enhanced series elastic energy storage and return, this could permit longer fascicle operating behavior which could in turn allow older adults to better accomplish tasks in the community that require enhanced push-off intensity (i.e. walking faster and walking uphill).

Maximum walking speed was significantly slower in older than in young adults. We posit that maximum walking speed has higher efficacy to assess functional walking ability than what can be inferred from preferred walking. For example, although we found no difference in peak ankle moment between older and young adults during normal walking, a significant interaction revealed that only young adults increased peak ankle moment to walk at their maximum speed. However, in neither group did fascicle length at peak ankle moment during normal walking correlate with maximum walking speed or the change in walking speed from preferred to maximum. This is surprising, as longer fascicles allude to a higher number of serial sarcomeres and thus higher possible contractile velocities. Despite this, prior literature in young adults has shown that fascicle length change behavior is relatively insensitive to changes in walking speed (Farris & Sawicki, 2012). While these muscle-level insights provide an entirely novel contribution, this is not the first evidence to suggest that maximum walking performance is disassociated from habitual locomotor patterns. For example, previous work has shown that strengthening the plantarflexor muscles in older adults elicits improvements in maximum walking speed but has little to no effect on habitual ankle joint kinetics or preferred walking speeds (Beijersbergen et al., 2017; Beijersbergen et al., 2013). We advocate for the more widespread use of dynamic *in vivo* ultrasound during functional tasks in aging research to better understand the mechanisms underlying cross-sectional differences and interventional outcomes.

There are several limitations to this study. First, our trial order prevented the impeding force condition from influencing preferred locomotor patterns, and ensured maximum exertion during Ramp. As such, we cannot exclude the possibility of ordering effects. Despite similarities in biomechanics during treadmill and overground walking (Riley et al., 2007; Watt et al., 2010), we also cannot be certain that use of a treadmill did not influence the muscle-level response. This study could also be strengthened by a larger sample to better power our independent-samples comparisons. In particular, we were unable to accept our hypothesis that older adults walk normally with shorter plantarflexor muscle fascicles than young adults, as this difference did not reach statistical significance. Finally, fascicle lengths measured *in vivo* during walking cannot provide direct evidence for where on the force-length curve older and young adults are actually operating. We tend to interpret the limited available literature (Mian, Thom, et al., 2007; Panizzolo et al., 2013) to suggest that older adults may operate further down the ascending limb of this relation during walking, which could in turn have implications for force generating capacity and ability to accomplish the more rigorous walking tasks as well as young adults. However, there is a critical need for empirical data to describe aging effects on fascicle (and sarcomere) length-tension behavior in the same human subjects as functional walking tasks such as those included in this study. Such data would allow us to gauge the extent to which reaching a fascicle shortening "limit", i.e. fascicles being too short to generate sufficient force, precipitates failure during demanding walking tasks.

CONCLUSION

In conclusion, we report that shorter gastrocnemius fascicle lengths in older adults associate with worse capacity to enhance push-off intensity in walking, even when controlling for isometric strength and subject anthropometrics. We also found that older adults undergo less relative fascicle shortening, especially in tasks which increase the propulsive demands of walking. These findings provide muscle-level insight for rehabilitation techniques that improve push-off intensity in older adults and assistive technologies designed to steer plantarflexor muscle fascicle operating behavior during functional tasks.

CHAPTER 5: THE EFFECTS OF A 6-WEEK HORIZONTAL IMPEDING FORCE TRAINING PROTOCOL ON PUSH-OFF INTENSITY IN OLDER ADULTS

INTRODUCTION

Preventing limitations in walking ability for the aging population is crucial for older adults to lead longer and more independent lives (Franz, 2016; Studenski et al., 2011). Those limitations are most often characterized by shorter steps and slower habitual speeds that are, in turn, attributed to reductions in mechanical output from muscle-tendon units spanning the ankle during push-off (i.e., "push-off intensity") (Franz, 2016; Prince, Corriveau, Hebert, & A. Winter, 1997; Winter et al., 1990). Conventional interventions to enhance that mechanical output (i.e., resistance training) are presumed to elicit muscle remodeling, increased force-generating capacity, and thus improved locomotor function. When prescribed in older adults, such countermeasures effectively improve isolated measures of leg muscle strength (Beijersbergen et al., 2017; Guizelini, de Aguiar, Denadai, Caputo, & Greco, 2018). Unfortunately, those strength gains generally fail to translate to functional improvements in habitual push-off intensity during walking (Beijersbergen et al., 2017; Mian, Baltzopoulos, et al., 2007; Persch et al., 2009; Watt et al., 2011a, 2011b). We propose that the lack of functional translation occurs because resistance training alone does not directly encourage access to newfound strength gains during gait. In particular, we suspect that the reduced habitual walking speed and push-off intensity in older adults are highly resistant to resistance training because of the established nature of habitual locomotor patterns. Therefore, there is a vital need for more targeted strategies designed to purposefully enhance push-off intensity in older adults.

The prescription of resistance training exercises in older adults has a longstanding history with measurable gains in muscle force-generating capacity (Guizelini et al., 2018). However, many well-designed strengthening interventions have shown limited translational results in terms of habitual push-off intensity (Beijersbergen et al., 2017; Kerrigan et al., 2001; Mian, Baltzopoulos, et al., 2007; Persch et al., 2009; Watt et al., 2011a). For example, a recent power training intervention for older adults reported relative gains in only maximum walking speed, but not habitual walking speed nor push-off intensity (Beijersbergen et al., 2017). Push-off intensity, which is routinely characterized by peak anterior or propulsive ground reaction force (GRF), ankle joint moment, and power, is particularly important in elderly gait. Specifically, older adults exhibit significant deficits in push-off intensity compared to their younger counterparts (Cofre et al., 2011; Conway & Franz, 2019; DeVita & Hortobagyi, 2000; Franz, 2016; Judge et al., 1996; Kerrigan et al., 1998; Prince et al., 1997; Winter et al., 1990) - deficits highly resistant to progressive strength training (Beijersbergen et al., 2017; Kerrigan et al., 2001; Mian, Baltzopoulos, et al., 2007; Persch et al., 2009; Watt et al., 2011a). However, changing habitual locomotor patterns may be fundamentally more challenging than improving maximum muscular or walking capacities. Indeed, Watt et al. (Watt et al., 2011a) found an analogous outcome following a 6-week hip flexor stretching protocol. This targeted intervention increased hip extension range of motion in older adults as designed; however, despite newfound mobility gains, participants generally failed to increase peak hip extension or push-off intensity during walking compared to baseline (Watt et al., 2011a, 2011b).

Horizontal impeding forces, usually applied via a waist-belt, can be used to systematically augment the mechanical output from muscle-tendon units spanning the ankle during the push-off phase of walking (Conway et al., 2018; Conway & Franz, 2019; Lewek, Raiti, & Doty, 2018; Penke, Scott, Sinskey, & Lewek, 2019). Indeed, in our recent application of horizontal impeding forces in older adults, we found that subjects immediately responded by increasing propulsive ground reaction forces (GRF) and ankle power output by as much as 71% and 20%, respectively (Conway & Franz, 2019). Those promising results suggest that horizontal impeding forces may provide the opportunity to more functionally target age-related deficits in push-off intensity in a step-by-step manner during walking not feasible using isolated muscle contractions in older adults. Indeed, because acute responses to horizontal impeding forces increase mechanical power from targeted muscles, repeated exposure may contribute to motor learning of a new, more desirable gait pattern (Reisman, Bastian, & Morton, 2010). Accordingly, we posit that horizontal impeding force gait training may more directly enhance push-off intensity during walking with the potential for tangible improvements in walking performance *and* habitual gait biomechanics.

Therefore, the purpose of this study was to investigate the preliminary efficacy of a 6-week horizontal impeding force training paradigm in otherwise healthy older adults. We first hypothesized that capacity measures (e.g., isometric strength, maximum walking speed, and 6-minute walk distance) would increase following a 6-week horizontal impeding force training intervention in older adults. We also hypothesized that habitual walking speed and biomechanical indicators of habitual push-off intensity (i.e. propulsive GRF and ankle moment and power) would increase.

METHODS

Subjects

11 healthy older subjects (age: 76±4 years, height: 171.5±9.5 m, mass: 74.3±12.5 kg, 6F/5M) participated in the intervention. The protocol was approved by the UNC Institutional Review Board and all subjects provided written informed consent before participating. Subjects had no neurological disorders or disease, had not suffered cardiovascular, neurologic or musculoskeletal injury in the previous 6 months, and could walk without an assistive device. To ensure that participants were not meeting activity level guidelines for older adults, as recommended by the US Department of Health and Human Services, we excluded potential participants if they participated in more than 150 minutes of moderate intensity or 75 minutes of vigorous intensity aerobic physical activity per week (U.S. Department of Health and Human Services, 2018). Subjects were also excluded if their preferred walking speed exceeded 1.4 m/s, or if they self-reported walking more than 10,000 steps per day. Prior to participation, subjects reported via health questionnaire performing vigorous activity 0.9±1.7 times a week, moderate activity 3.4±2.7 times a week, and light activity 4.4±3.0 times a week for, on average, at least 15 minutes per session. We also monitored daily step counts using wearable activity monitors before and during the 6-week training protocol (i.e., Charge 3, Fitbit, CA).

Pre and Post-Intervention Assessments

During the initial baseline ("Pre") and final ("Post") sessions, we recorded subjects preferred (i.e. habitual) and maximum safe walking speeds as the average of three times taken to traverse a 30 m and 2 m walkway, respectively. After a 5-minute warm up on the treadmill, subjects then performed ramped isometric voluntary contractions of the ankle plantarflexors while seated in a dynamometer (Biodex, Shirley, NY). The ankle (10° dorsiflexion) and knee (~20° flexion) angles were selected to replicate that near the push-off phase of walking (Conway & Franz, 2019; McClelland, Webster, Feller, & Menz, 2011). Subjects were verbally encouraged to reach their maximum effort during two, 4-second ramped contractions separated by at least one minute of rest. Peak ankle moments were calculated from the average of the two maximum contractions. In addition, subjects completed a 6-minute walk test (6MWT) where they were instructed to walk as far as possible in 6 minutes along a 30 m walkway (Ng, Yu, To, Chung, & Cheung, 2013).

During Pre and Post sessions, we also collected 2 minutes of kinematic and kinetic data during habitual speed ("Pref") walking on an instrumented treadmill (Bertec Corp., Columbus, OH). In a separate trial, starting from rest, we accelerated the treadmill at a constant rate of 0.2 m/s^2 until we reached subjects' maximum safe overground speed, which was maintained for approximately 5 seconds. For these treadmill trials, 3D trajectories of 31 retroreflective markers recorded at 100 Hz on the pelvis and lower limbs were recorded using a 14-camera motion capture system (Motion Analysis Corp. Santa Rosa, CA) while 3D GRF data were simultaneously recorded at 1000 Hz. Data were then filtered using 4^{th} order low-pass Butterworth filters with cutoff frequencies of 6 Hz (marker data) and 100 Hz (GRF data). We used a standing trial and functional hip joint centers from right and left leg circumduction tasks (Piazza et al., 2001) to scale a seven segment, 18 degree-of-freedom model of the pelvis and lower limb (Arnold et al., 2010) . Finally, we used these scaled models and an inverse dynamics routine described in detail previously to estimate hip, knee and ankle joint angles, and ankle moments and powers (Arnold et al., 2010). We then averaged time-normalized right leg outcome measures across the trial duration (i.e. 2 minutes for habitual speed trials and 5 seconds for maximum speed trials).

Impeding Force Training Protocol

After baseline testing, subjects started a 6-week, twice per week, horizontal impeding force training protocol. We selected the duration of this protocol based on intervention recommendations of 4-6 weeks to elicit locomotor function improvements (Mian, Baltzopoulos, et al., 2007). For this training protocol, we used a custom motor-driven horizontal impeding force system (**Fig. 1A**) described in detail previously (Conway et al., 2018; Conway & Franz, 2019). Briefly, the system consists of a servo motor (Kollmorgen, Radford VA) controlled in real-time using a LabVIEW interface (cRIO-9064, National Instruments, Austin, TX) in series with a cable connected to a waist belt worn by subjects. In each training session, subjects walked at their habitual speed for 20 minutes against submaximal horizontal impeding forces, prescribed as follows.

All subjects first completed a 20-minute training session with a horizontal impeding for of 3% BW, based on past experience and pilot testing (Conway & Franz, 2019; Gottschall & Kram, 2003). We then progressively increased impeding force levels in 0.5% BW increments at 5-minute intervals to maintain a moderate activity level based on RPE (i.e. 4-6). We also monitored subjects' heart rate (HR) during each walking session. We calculated maximum HR as 220 – subjects' age, and HR reserve as maximum HR – resting HR. We estimated resting HR while seated for 5 min via a Fitbit. During each training session, we ensured subjects' HR remained less than 70% of their HR reserve(Aguiar et al., 2018).

Statistical Analysis

Our main outcomes were capacity measures (e.g., isometric plantarflexion strength, maximum walking speeds, and 6-min walk test distance) and habitual measures (i.e., habitual walking speed, GRF, ankle moment and power). Shapiro-Wilks tests first confirmed normal distribution for all outcome measures. We then assessed the efficacy of the impeding force training intervention (i.e., baseline versus post-training assessments) using paired-samples t-tests using an alpha level of 0.05. We also report Cohen's d effect sizes for all primary comparisons.

RESULTS

Subjects completed 100% of a total of 12 sessions across 6 weeks. Pre sessions were conducted 3±2 days before, and Post sessions were conducted 2±2 days after, the 12 training sessions. The average time between Pre and Post sessions was 42 ± 3 days. Impeding force training levels increased from 3% BW to 4.6%±1% BW on average by the final training session (**Fig. 17B**). Subjects walked on average 7124±855 steps per day outside of the lab during the intervention, which is comparable to activity levels a week prior to the intervention (6911±1512 steps/day, p=0.571). Changes that follow characterize the overall effect of the 6-week intervention (i.e., Pre vs. Post). For example, isometric plantarflexor strength and maximum walking speeds increased on average by 18% (1.13±0.40 vs. 1.34±0.32 Nm/kg) and 10% (1.82±0.25 vs. 2.00±0.25 m/s), respectively (p-values≤0.002, d≥0.508, **Fig. 18**). Although a 15% increase in maximum speed peak ankle power generation following the 6-week training intervention was not significant (3.97±0.92 vs. 4.55±1.42 W/kg, p=0.252, d=0.485), subjects did increase their 6MWT distance on average by a significant 9% (546.06±76.24 vs. 592.50±66.22 m, p=0.001, d=0.650, **Fig. 18**).

Habitual walking speed increased by a modest 4% on average (1.25±0.10 vs. 1.30±0.11 m/s, p=0.095, d=0.453, **Fig. 19**). Likewise, neither habitual propulsive ground reaction force (18.36±2.90 vs. 19.30±2.94 %BW, p=0.148, d=0.322) nor stride length (1.35±0.17 vs. 1.37±0.14 m, p=0.612, d=0.128) changed significantly. At habitual walking speed, the peak ankle moment and ankle power significantly increased on average by 10% (1.23±0.15 vs. 1.35±0.16 Nm/kg) and

15% (2.62±0.69 vs. 3.02±1.00 W/kg) respectively (p-values ≤0.036, d≥0.466, **Fig. 20).** We found no significant differences in habitual ankle, knee, and hip joint angles (**Fig. 21**).

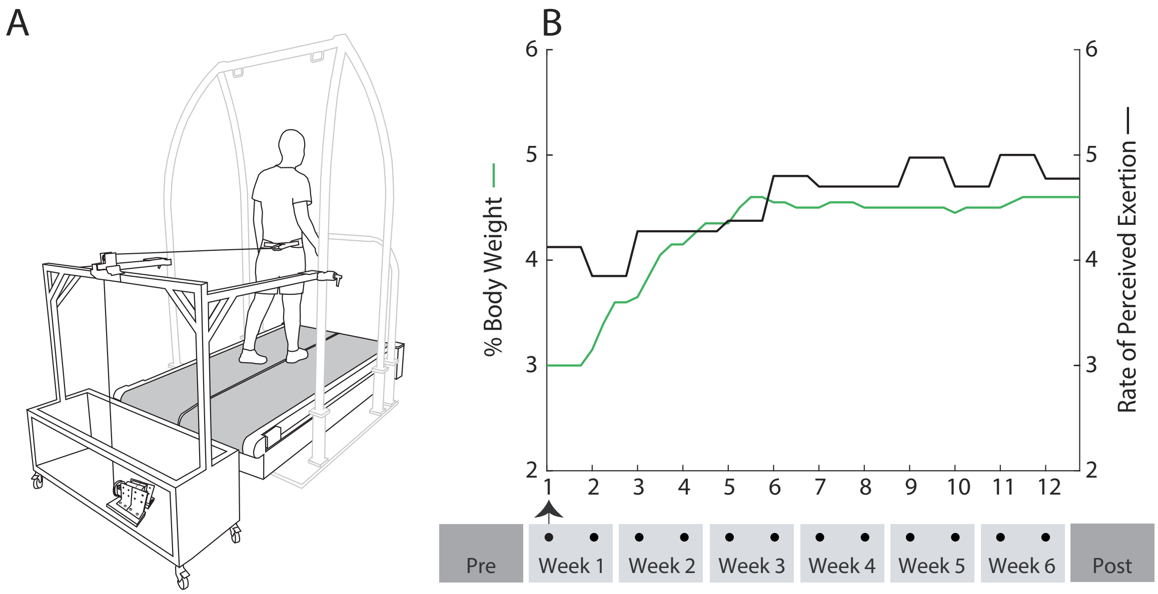


Figure 17: (A) Schematic showing experimental approach and the schedule for horizontal impeding force training**. (B)** Group-average impeding force training levels in % bodyweight (blue) and subject rate of perceived exertion (green) across 12 walking sessions (i.e., 6 weeks) of impeding force training.

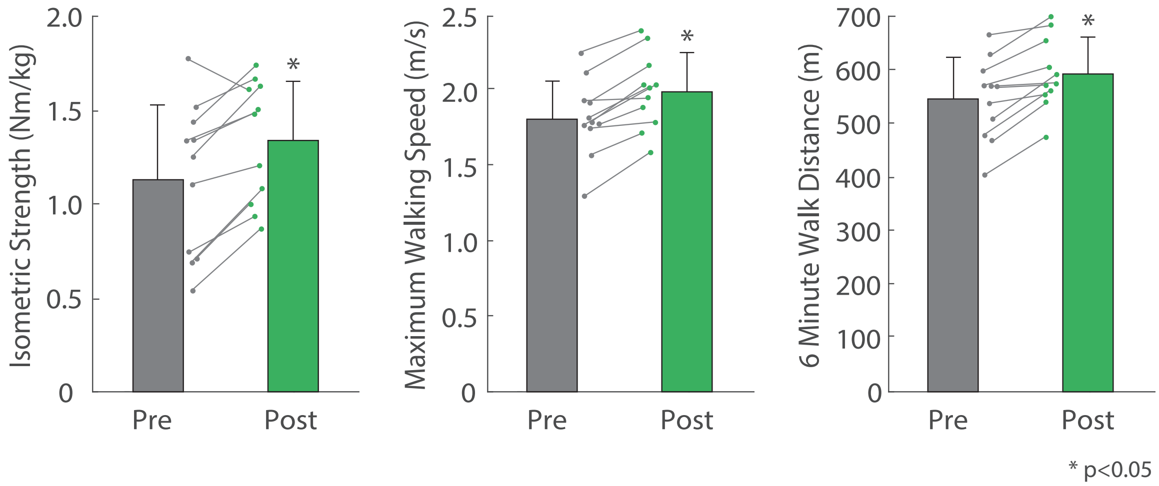


Figure 18: Individual and group-average (standard deviation) isometric plantarflexor strength, maximum walking speed, and 6-minute walk test distance for Pre (i.e., at baseline) and Post sessions (i.e., after 6 weeks of impeding force training). Single asterisks (*) represent significant Post-Pre differences (p<0.05).

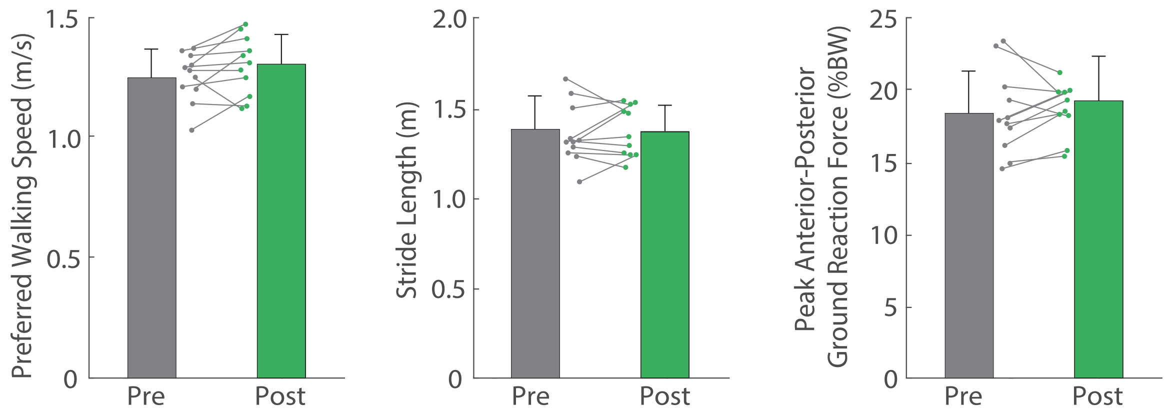


Figure 19: Individual and group-average (standard deviation) habitual walking speed, habitual stride length, and habitual peak anterior ground reaction force for Pre (i.e., at baseline) and Post sessions (i.e. after 6 weeks of impeding force training).

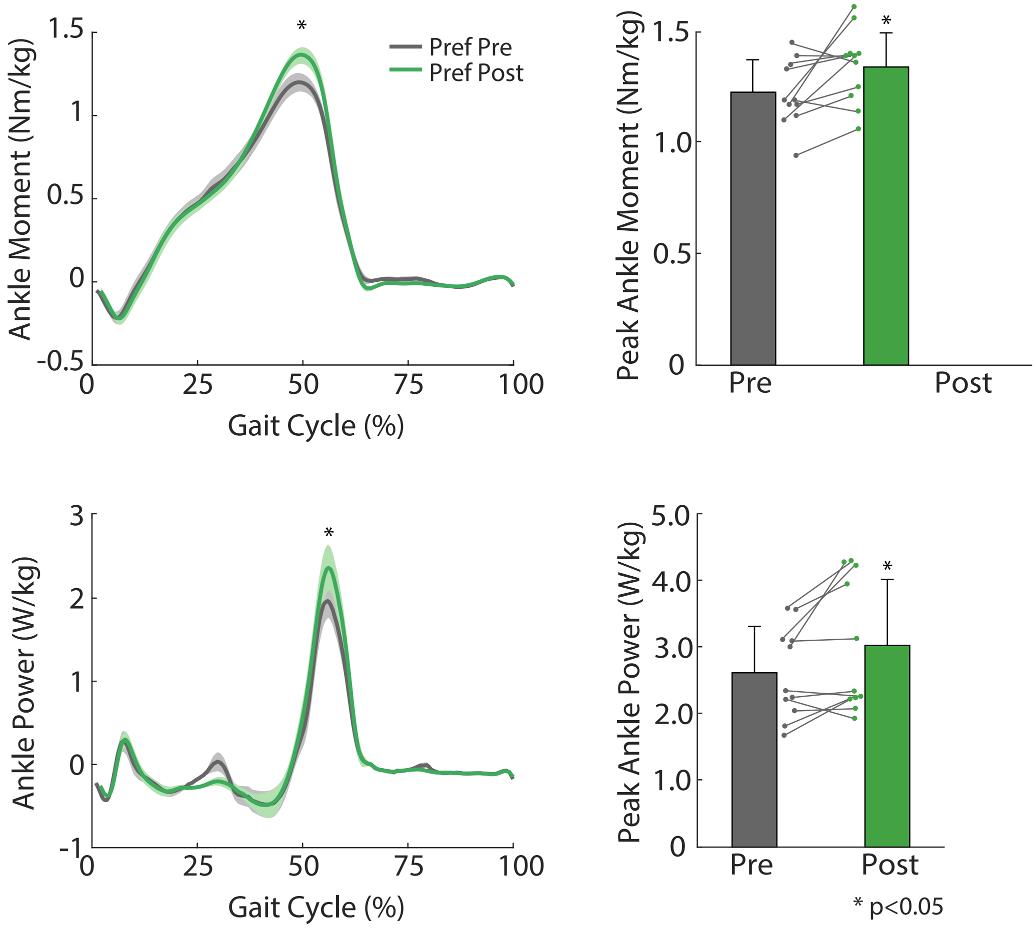


Figure 20: Group-average (standard deviation) peak ankle joint moment and peak ankle joint power measured during habitual speed walking for Pre (i.e., at baseline) and Post sessions (i.e., after 6 weeks of impeding force training), plotted against an average gait cycle from heel-strike to heel-strike. Single asterisks (*) represent significant Post-Pre differences ($p<0.05$).

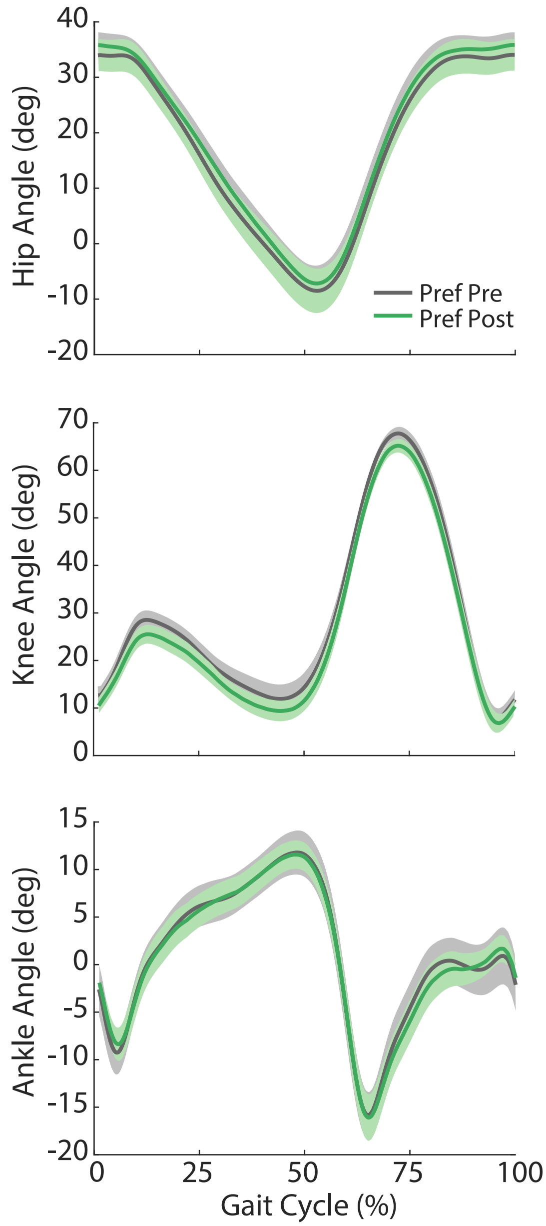


Figure 21: Group-average (standard deviation) hip, knee and ankle joint angles measured during habitual speed walking for Pre (i.e., at baseline) and Post sessions (i.e., after 6 weeks of impeding force training), plotted against an average gait cycle from heel-strike to heel-strike.

DISCUSSION

We investigated the preliminary efficacy of a 6-week impeding force training paradigm in healthy older adults that had not regularly met physical activity guidelines(U.S. Department of Health and Human Services, 2018). First, our older adults averaged deficits in propulsive ground reaction force, ankle moment, and ankle power of 13%, 22% and 32%, respectively, prior to training compared to previously published data in young adults walking at comparable speeds (Conway & Franz, 2019). We would thus consider our older adult cohort representative of those for which targeted intervention may be beneficial, at least in terms of their push-off intensity. Our findings supported our first hypothesis; isometric strength, maximum walking speed, and 6-minute walk distance increased significantly following a 6-week horizontal impeding force training intervention in older adults. Corresponding increases in habitual walking speed, however, were not statistically significant. Moreover, neither habitual propulsive GRF nor stride length were affected by the intervention. However, as a significant contribution of this work and in partial support of our second hypothesis, habitual ankle moment and power increased significantly following 6 weeks of horizontal impeding force training. Taken together, this suggests that impeding force training simultaneously improves maximum capacity measures while also encouraging access to newfound strength gains during habitual walking.

Measures of maximum muscular and walking capacity (i.e. isometric strength, maximum walking speed, and 6-minute walk test distance) have previously been receptive to conventional intervention (Liu & Latham, 2009; Papa, Dong, & Hassan, 2017; Sipila, Multanen, Kallinen, Era, & Suominen, 1996). Not surprisingly, resistance training programs designed to improve maximum muscle force-generating capacity do improve isometric and/or isokinetic strength(Beijersbergen et al., 2017; Liu & Latham, 2009). A recent systematic review and meta-analysis reported that resistance training can be expected to yield average strength gains of ~18% when prescribed in older adults(Guizelini et al., 2018). Those cumulative results are comparable to the plantarflexor strength gains we report here. Similarly, strength-based interventions have also successfully transferred to ~6-11% improvements in maximum walking speed (Beijersbergen et al., 2017; Helbostad, Sletvold, & Moe-Nilssen, 2004; Nicholson, McKean, & Burkett, 2015; Sipila et al., 1996), comparable to the 10% increase reported here following 6 weeks of horizontal impeding force training. One explanation may be that improved plantarflexor strength increases the maximum capacity for ankle power generation during walking. Indeed, post-hoc testing revealed that improvements in plantarflexor strength in our cohort explained ~53% ($r=0.730$, $p=0.005$) of the change in peak ankle power generated at maximum speed. Finally, the 6-minute walk test, a clinically-viable test with extensive application in older adults(Harada, Chiu, & Stewart, 1999), assessed the translation of these gains in mechanical output to walking endurance. Previous strengthening interventions for older adults have shown improvements of ~5-10% in 6MWT distance (Bastone Ade & Jacob Filho, 2004; Capodaglio et al., 2005; Earles, Judge, & Gunnarsson, 2001; Rubenstein et al., 2000). In addition to their improvements in strength and maximum walking speed, our older adults increased their 6-min walk distance by +9%. One could thus interpret horizontal impeding force training as a more functional form of resistance training with similar efficacy for improvements in strength and maximum walking speed that also transfer to improved walking endurance.

Alternatively, measures of habitual walking performance (i.e., preferred walking speed) and biomechanical determinants of push-off intensity (i.e., propulsive ground reaction force and ankle moment and power output) appear highly resistant to intervention in older adults (Franz, 2016; Mian, Baltzopoulos, et al., 2007). Previous studies using resistance training have failed to translate gains in muscle force generating capacity into improved habitual walking performance or push-off intensity (Beijersbergen et al., 2017; Buchner et al., 1997; Cao et al., 2007; Earles et al., 2001; Granacher et al., 2011; Hartmann et al., 2009; Watt et al., 2011a, 2011b). Perhaps not surprisingly, then, our cohort of older adults only tended to improve their habitual walking speed by a modest 4%, or 0.05 m/s, on average – an increase that did not reach significance. However, we cannot exclude the potential that older adults with more substantial reductions in habitual walking speed would have exhibited larger improvements. Indeed, despite obvious deficits in push-off intensity, our subjects adopted habitual speeds that many would consider relatively similar to that found in younger adults. We also found no significant change in peak propulsive ground reaction forces following 6 weeks of impeding force training. This too may not be especially surprising because older adults did not adopt longer stride lengths during habitual walking in their Post session, and their stride length during the baseline session was not different from that which we have measured in young adults (Conway & Franz, 2019).

Ankle power generation is a crucial determinant of the age-related decline in habitual push-off intensity, which is particularly resistant to conventional intervention. More specifically, older adults, including those in this study, generally exhibit characteristic ~10-30% deficits in habitual ankle moment and power output (Conway & Franz, 2019; DeVita & Hortobagyi, 2000; Prince et al., 1997; Winter et al., 1990). Relatively few studies have investigated the intervention-based changes in biomechanical determinants of push-off intensity in older adults. However, a recent but rigorous power training intervention failed to increase older adults' habitual peak ankle joint moments or powers during push-off (Beijersbergen et al., 2017). As one of the most significant contributions of our study, we found that older adults significantly increased their peak ankle moment and power by 10 and 15%, respectively, when walking at their habitual speeds following impeding force training – a relatively unprecedented outcome. Accordingly, we suggest that providing an intervention that *functionally* targets the muscles responsible for push-off intensity (i.e., the plantarflexors) may be capable of mitigating well-documented age-related declines in habitual push-off intensity.

The logical next step in this line of translational research is a randomized control trial in order to further substantiate our promising, but preliminary, conclusions. Specifically, we recommend a larger cohort of older adults, along with a treadmill walking control group to isolate the effects of horizontal impeding force training alone. In addition, we recommend further study to characterize the dose response characteristics to better enable personalized prescription of horizontal impeding force levels for older adults. Indeed, our cohort of older adults showed significant improvements in key outcome measures for which large age-related deficits were present (i.e., ankle moment and power). For those with reduced speed or clinically-relevant deficits in stride length, there may be differential responses to impeding force training - namely, larger deficits may give rise to larger gains. Another strength of our real-time, motor driven system is the potential for gait-synchronized control, with a training paradigm implemented unilaterally, thereby preferentially training an affected limb during rehabilitation. Indeed, such an approach can be applied to individuals with unilateral propulsive deficits for whom passive constant impeding force resistance has shown some therapeutic benefit (i.e., persons following stroke (Lewek et al., 2018; Penke et al., 2019)). Ultimately, we present this functional training paradigm as a possible alternative to conventional resistance or power training protocols for those with deficits in push-off intensity who are generally prescribed strength-based rehabilitation. Further, we envision trade-offs relevant to widespread community use between the need for precise force regulation versus lower cost solutions to horizontal forces evident in the published literature (e.g., bungee or weight-based forces (Lewek et al., 2018; Penke et al., 2019; Zirker, Bennett, & Abel, 2013)).

There are several limitations of this study. First, we did not include a control group for comparison. As such, we cannot rule out the possible training effects of treadmill walking itself, independent of impeding forces. Another limitation of this study is that we changed training load based on the RPE responses of our older adult subjects which, by design, is a subjective measure of intensity, and thus open to misinterpretation. For this reason, we took objective measures of intensity via HR monitoring, which generally corresponded with RPE measures. This intervention also included no additional follow-up, we are thus unable to make conclusions regarding the retention of these effects. We also report a relatively small group of older adults - future studies would benefit from a larger cohort to promote responder subgroup analyses toward personalized prescription. Finally, while we excluded subjects based on activity level, our subjects were still relatively high functioning. For example, our cohort showed no significant deficits in habitual gait speed, which could explain a possible ceiling effect following training. We predict that a relatively lower-functioning cohort of older adults would exhibit greater gains in metrics of capacity and habitual gait performance.

CONCLUSION

In conclusion, we report improvements in clinical and biomechanical metrics of both maximum and habitual walking performance as a result of a 6-week impeding force training protocol. Specifically, isometric plantarflexion strength, maximum walking speed, and 6-minute walk distance all increased between Pre and Post sessions. In addition, unlike previous conventional interventions (Beijersbergen et al., 2017; Mian, Baltzopoulos, et al., 2007; Persch et al., 2009; Watt et al., 2011a, 2011b), habitual peak ankle moment and power generation increased significantly after 6 weeks of impeding force training. Ultimately, we interpret these results to support our premise that, by functionally targeting push-off intensity during walking directly, in a manner presumed meaningful to participants, the use of a horizontal impeding force in older adults improved their maximum muscular and walking capacity while encouraging continued access to newfound plantarflexor strength gains during habitual walking.

CHAPTER 5: CONCLUSIONS

The purpose of this dissertation was first to design and implement a motor driven impeding force system to first investigate push-off intensity at the limb-, joint-, and muscle-levels during walking in older adults, and thus functionally limiting impairments of elderly gait. Second, to test the efficacy of a 6-week impeding force training protocol in improving push-off intensity during walking for older adults. Combined, these studies contributed to our mechanistic understanding of deficits in push-off intensity in older adults and informed rehabilitation programs which could contribute to improvements in mobility, independence, and quality of life in our older adult population. Looking ahead, the broader implications of this work include the application of these studies to clinical populations such as cerebral palsy, multiple sclerosis, and persons following stroke.

Study One

In my first study, we sought to improve our joint-level understanding of the functional utilization of propulsive capacity during human walking in young subjects, with an emphasis on the plantarflexor muscles. We used horizontal impeding forces to quantify propulsive capacity during human walking - an approach that may have implications for the prescription of interventions for individuals with walking ability limitations exemplified by reduced push-off intensity. The reference young adult data we reported provide an important benchmark for future translational work and, thereafter, clinical decision making in gait rehabilitation. Indeed, we envisage this “biomechanical stress test” being applied to other populations for the more personalized prescription of rehabilitation. This technique may also be leveraged to test the true limits of innovative assistive devices such as prostheses and exoskeletons in a functional way.

Study Two

The logical next step for this research was to leverage our ramped maximum horizontal impeding force protocol in an older adult population, to investigate the true limitations of elderly gait. We found that despite walking with hallmark age-related deficits in propulsive ground reaction force, trailing limb positive center of mass work, trailing leg and hip joint extension, and ankle power generation, older adults are capable of overcoming those deficits when the propulsive demands of walking are increased to their maximum. In contrast, older adults appear physically incapable of fully overcoming deficits in peak ankle moment during walking, alluding to a genuine functionally limiting impairment. Future work may also use this paradigm to investigate functionally limiting impairments in clinical populations.

Study Three

In my third study, we sought to gain an improved muscle-level understanding of the underlying age-related reductions in peak ankle moment found in study two. We found that shorter gastrocnemius fascicle lengths in older adults associate with worse capacity to enhance push-off intensity in walking, even when controlling for isometric strength and subject anthropometrics, likely due to muscle length-tension relation. We also found that older adults undergo less relative fascicle shortening, especially in tasks which increase the propulsive demands of walking. These findings provide muscle-level insight for rehabilitation techniques that improve push-off intensity in older adults and assistive technologies designed to steer plantarflexor muscle fascicle operating behavior during functional tasks.

Study Four

Finally, we investigated the efficacy a 6-week impeding force training paradigm in improving push-off intensity during walking in older adults. We reported improvements in clinical and biomechanical metrics of both maximum and habitual walking performance as a result of a 6-week impeding force training protocol. Specifically, isometric strength, maximum walking speed, and 6-minute walk test distance all increased between Pre and Post sessions. In addition, unlike previous conventional interventions, habitual speed ankle power significantly increased after 6 weeks of impeding force training. Taken together, this suggests that impeding force simultaneously improves maximum capacity while also encouraging access to these newfound strength gains. Future work in this line of translational research is a full randomized control trial in order to further substantiate our promising but preliminary conclusions. Ultimately, we present this paradigm as a possible alternative to conventional resistance or power training protocols for those generally prescribed strength-based rehabilitation. Moving forward, this paradigm could have broad implications for clinical populations previously prescribed strength-based rehabilitation programs (e.g., cerebral palsy, persons following stroke, or older adults)

APPENDIX 1: EFFECTS OF A 6-WEEK HORIZONTAL IMPEDING FORCE TRAINING PROTOCOL ON GASTROCNEMIUS CROSS-SECTIONAL AREA

The plantarflexors (i.e. gastrocnemius and soleus muscles) are responsible for the majority of the push-off intensity during walking. Due to an increased propulsive demand, horizontal impeding forces during walking specifically challenge the plantarflexor muscles. In particular, the gastrocnemius muscles have previously been implicated as the most important muscles during walking in terms of forward propulsion (Gottschall & Kram, 2003). Thus, we hypothesized that medial gastrocnemius cross-sectional area would increase in response to 6 weeks of impeding force training.

In a cohort of 10 healthy older adults (age: 75±4, height: 171.5±10.2 m, mass: 73.3±13.4 kg, 6F/4M), we used transverse ultrasound imaging (Echoblaster 128, 10 MHz, Telemed, Vilnius, Lithuania) at approximately 50% of the overall medial gastrocnemius muscle length before ("Pre") and after ("Post") a 6-week horizontal impeding force training protocol (**Fig. 17**). We then used ImageJ to estimate medical gastrocnemius anatomical cross-sectional area. The same investigator analyzed all images. We compared Pre and Post intervention outcomes statistically using a paired samples t test, with an alpha level of 0.05.

On average, medial gastrocnemius anatomical cross-sectional area increased by a significant 14% (12.81±4.24 cm^2 vs. 11.20±4.10 cm^2, $p=0.034$, **Fig. 22**) in our older adult cohort after 6 weeks of horizontal impeding force training. Furthermore, increased gastrocnemius anatomical cross-sectional area positively correlated with plantarflexor strength gains ($r=0.564$, $p=0.045$).

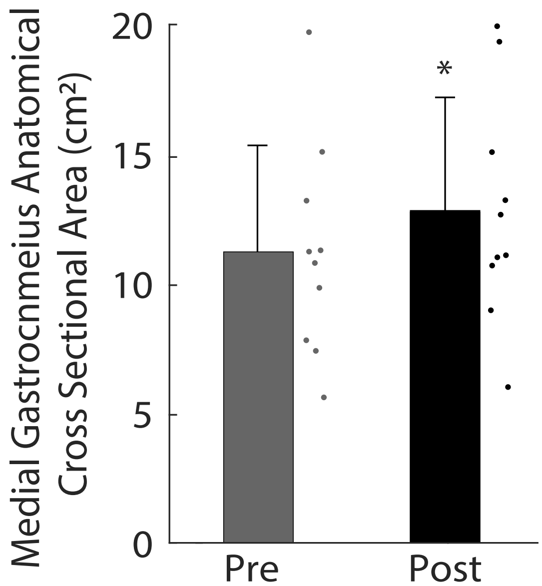


Figure 22: Group average (standard deviation) medial gastrocnemius anatomical cross-sectional area at Pre (i.e. baseline) and Post sessions (i.e. post 6-week impeding force training). Single asterisks (*) represent a significant difference from Pre ($p<0.05$).

APPENDIX 2: EFFECTS OF A 6-WEEK HORIZONTAL IMPEDING FORCE TRAINING PROTOCOL ON METABOLIC ENERGY EXPENDITURE DURING HABITUAL SPEED WALKING

In a cohort of 8 healthy older adults (age: 76±4, height: 171.1±10.1 m, mass: 76.5±13.0 kg, 4F/4M), we used a portable metabolic system (K5 COSMED, Italy) to record oxygen consumption (VO_2) at habitual speed before ("Pre") and after ("Post") a 6-week horizontal impeding force training protocol (**Fig. 17**). Prior to walking, we collected a 5 minute quiet standing trial. During habitual speed walking, we collected 7 minutes of metabolic data. For those whose habitual walking speed differed by 3% or more from baseline, we recorded a second, "new" habitual speed trial of 7 minutes. For all trials, we averaged the final 2 minutes, and normalized to body mass. Using the Brockway equation, we calculated net metabolic power by subtracting standing metabolic data from that during habitual speed walking (Brockway, 1987). We compared Pre and Post intervention outcomes statistically using a paired samples t test, with an alpha level of 0.05.

Older adults' normalized oxygen consumption and net metabolic power at baseline habitual speed was similar before and after the 6-week horizontal impeding force training protocol (15.79±2.65 vs. 15.53±2.35 mL/kg/min, p=0.678, and 3.88±0.69 vs. 3.88±0.59 W/kg, p=0.986, respectively **Fig. 23**). For a subset (n=6) of our cohort, habitual walking speed increased by more than 3% between Pre and Post (+8%, 1.37±0.11 vs. 1.27±0.11 m/s, p=0.002). Interestingly, For this subset, older adults' oxygen consumption and net metabolic power also increased by 14% and 15% on average (17.42±3.24 vs. 15.29±2.73 mL/kg/min, p=0.046 and 4.43±0.87 vs. 3.86±0.69 W/kg, p=0.008) at their new habitual walking speed compared to baseline. Thus, older adults chose a faster speed after 6-weeks of impeding force training despite an increased metabolic cost.

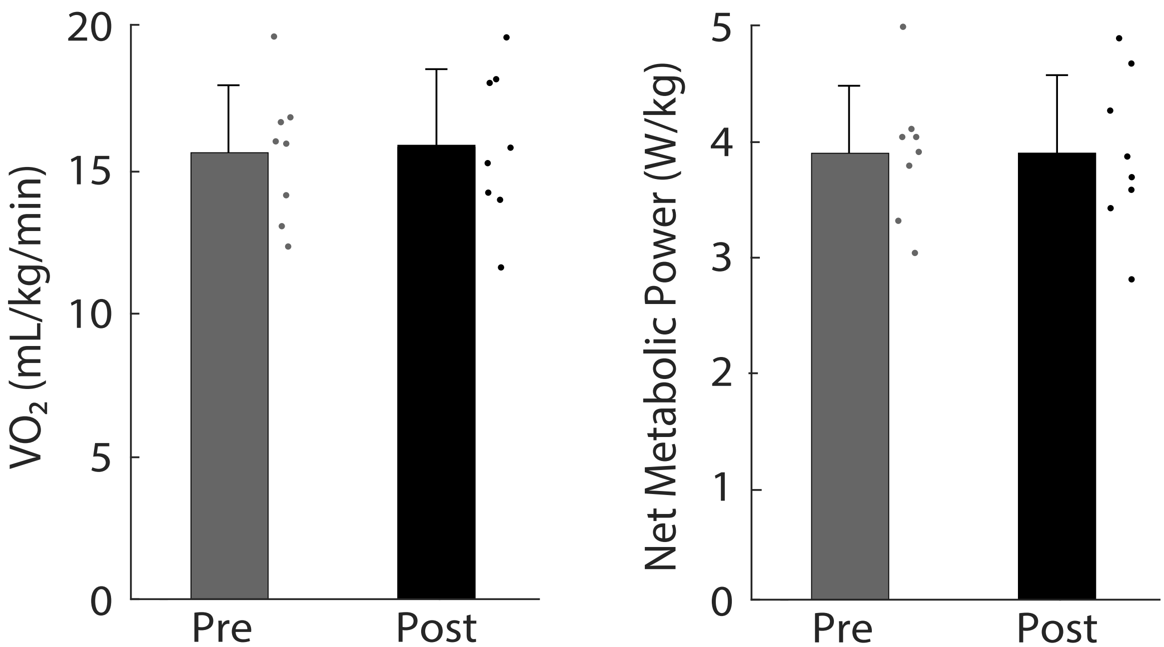


Figure 23: Group average (standard deviation) normalized oxygen consumption (VO_2) and net metabolic power (W/kg) during habitual speed walking at Pre (i.e. baseline) and Post sessions (i.e. post 6-week impeding force training).

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